Author’s responses

We would like to thank Referee #1 for the time he/she invested to give his/her thoughtful and constructive comments. For clarity, we have copied his/her comments and placed our answers below each comment.

GENERAL COMMENTS

Referee: A general problem I have with this manuscript is the length of many sections and the wordiness of many paragraphs. The abstract alone comes in at ~430 words and could be substantially shortened (no need to describe site replication for instance). The “Materials and Methods” section for instance is extremely long (9.5 pages) and should be streamlined.

Answer: In order to address the referee’s concerns, we shortened the abstract. As suggested we took out the replication and the timing of sampling (page 2, lines 10-15 of the original manuscript and removed the sentences about N-oxide losses of the applied N in the abstract (page 3, lines 1-3 of the original manuscript). We also streamlined section 2.1 “Study area, experimental design and management practices”. We took out details regarding the management practices, which have been reported in our earlier paper (Hassler et al., 2015) and which have been not directly relevant in the present manuscript (page 8, lines 6-15 of the original manuscript). Lastly, we shortened section 2.3 “Statistical analysis” (see answer to detailed comment #13 below) and put the detailed statistical description to Appendix A.

Referee: In contrast, the discussion in particular would benefit from greater detail (and discussion with results from other regions of the world).

Answer: We indeed compared our results on soil N-oxide fluxes with measurements from other parts of the world (page 19, lines 8-9; page 20, lines 1-5; pages 21-22, lines 24-4; page 22, lines 15-18). This we elaborated also in our answer to comment #27 below).

Referee: Also to me, a clear site/ replicate nomenclature would better guide the reader through the text as the full measurement setup is rather complex (two soil landscapes, 4 land uses, 3 chamber positions at each site, 4 replicates). For instance, if the authors could define some site abbreviations (e.g., reference land uses: F (forest), JR (jungle rubber); converted uses: RP (rubber plantation), PP (oil palm plantation), they could simple use to those instead to repeat the site attributes or be overly descriptive. This is also true for the naming of the three within-site chamber positions (currently: a, b, c). While their properties are described in the text, and also in the caption of table 4 it makes the digestion of the data presented unnecessary hard for the reader (maybe: F1 (fertilised area position 1 / 0.3m from stem), F2 (fertilised area position 1 (0.8m from stem), NF (non fertilised: 4.5m from stem). In lengthy paragraphs it is easy to get lost and scramble to read up what i.e. position b represents (same for the reference to the proposed hypothesis’).

Answer: We agree with the suggestion to use more descriptive abbreviations for chamber positions a, b and c. To address this concern, we introduced the abbreviations: F1 = chamber at 0.3 m from the

tree base with incidental fertilization, F2 = fertilized chamber at 0.8 m from the tree base, NF = non-fertilized chamber location at 4-4.5 m from the tree base (page 10, lines 5-10 and Tables 2 & 4). We also, as suggested, included abbreviations for the hypotheses (H1 and H2) (pages 5-6, lines 21-1) and pointed to these abbreviated hypotheses in the discussion to remind the reader how we linked our findings with the hypotheses (e.g., page 20, lines 14-15).
On the other hand, we did not use abbreviations for the land uses in order to avoid confusions with all the abbreviations.

Referee: Furthermore, I feel that reorganising and cleaning the tables would help the better digest the main results presented. Table A1 & A2 should be combined and added to the main text.
The figures are appropriate, but could also be improved, too (see detailed comments).

Answer: Please find our answers regarding this comment below (detailed response).

DETAILED RESPONSE:

Referee: In the following I'd like to suggest some changes to the tables (often admittedly personal preference)

Table 1.

- *Referee: Shorten the caption (16 lines of description).*

  Answer: The reason why the table titles are long is because in Biogeosciences, the table format must not have a footnote. This table title would have been short if the parts on statistical tests and identifiers can be placed as a footnote.
  We shortened the table titles (Tables 1-4) by taking out details on the measurement period, which are now put in Appendix Table A1 (as suggested by reviewer 2). The table title, however, has to be succinctly correct without too much reference to the text, as one of the criteria of a Table is that it has to be completely understandable without referencing too much to the main manuscript.

- *Referee: Also a column with number of samples (n) would help the reader to assess the robustness of the given average emission.*

- Answer: We included this information directly after the SE on the first line of the table title in order to minimize columns with anyway the same entry for n = number of 'real' replicate sites or plots per land use.

- *Referee: I would suggest to round to the first decimal to reduce visual clutter (esp. with the group identifiers presented in the table)*

- Answer: We agree with the suggestion and reduced the decimal place to one.

Table 2

- *Referee: The chamber location identifiers a, b and c do not help the reader. Either also identify the distance to the tree in the table or use descriptive abbreviations*

- Answer: As the reviewer suggests in the general comments #3 above, we introduced the abbreviations: F1 = chamber at 0.3 m from the tree base with incidental fertilization, F2 = fertilized chamber at 0.8 m from the tree base, NF = non-fertilized chamber location at 4-4.5 m from the tree base.

- *Referee: Again, indicate the number of measurements considered*

  Answer: The number of measurements is already indicated in the table title (line 3), and also the number of replicates is given in table title (line 1).

- *Referee:* Given the lack of NO data for 4 of the 6 sampled sites, maybe another organization would be better.
  For instance:
  Table 2a (N2O) – columns:
  Oil palm site / ch pos / N2O (clay Acrisol) / N2O (loam Acrisol)

  Table 2b (NO)- columns (with oil palm sites given as NO column identifier (?):
  CH pos / NO (clay Acrisol) / NO loam Acrisol

- Answer: Although this is generally a very good suggestion, we are convinced that the given structure of the table is also reasonable because of the following reasons:
  At a glance it is possible to see the differences in NO and N_2O fluxes for the sites where both gases were measured.
  The structure follows that of Table 1, to which the reader can easily cross-reference.
  To reduce clutter and improve ease in reading, the values are rounded off to one decimal place.

Table 3./4.

- *Referee: They could go into the appendix*

- Answer: We put all supplementary information now in Appendix A and Appendix Tables A1-A3. We decided to keep Tables 3 and 4 in the main manuscript because one of our objectives is to determine the controlling factors of soil N-oxide fluxes. These tables show the important controlling factors in the different land uses and also following fertilization.

- *Referee: Table 4 should be split into N2O and NO data (see Table 2)*

- Answer: Splitting Table 4 into two for these two gases will increase unnecessarily the number of tables, when in fact N_2O and NO can simply be put in the same table and it is easy to read this table for these two gases. This Table has similar structure as Table 3 in our earlier study (Hassler et al. 2015), published in Biogeosciences, where the two gases, CO_2 and CH_4, are put in the same table with their soil controlling factors.

Table A1/A2.

- *Referee: Shorten caption*

- Answer: In case of Table A1 (now Table A2 in the revised manuscript), we addressed this concern by taking out the information on the statistical analysis because the significant differences among land uses and between landscapes do not play a role on how we discussed the influence of these parameters on soil N-oxide fluxes.
- In case of Table A2 (now Table A3 in the revised manuscript), we addressed this concern by taking out the information about their measurement period, since this was also described in the methods (page 12, lines 11-14). We kept the statistics in this case because we refer to differences in soil mineral N content in our discussion (page 22, lines 19-23).

- *Referee: Combine A1 and A2 into one table and add it into main document as a site description/ reference for the reader.*

- Answer: We are convinced that these tables should stay separated for clarity reasons:
  First, the data in Table A1 (now Table A2) are used for the determination of spatial controls on annual soil N_2O fluxes and are only determined once, while the data in Table A2 (now Table A3) were determined concurrently with the soil N-oxide flux measurement (page 12, lines 11-14) and are used for determination of temporal controls on monthly measured soil N_2O fluxes (section 3.3).
  Second, a general site description is given in section 2.1, and Table A2 not aimed to describe the site but to give supporting data, which show correlations with annual soil N_2O fluxes.

- *Referee: Round WFPS, NH4 and NO3 to one digit to reduce clutter*

- Answer: We rounded the values to one decimal place.

- *Referee:* This might be personal preference, but maybe remove the significance letters, too (they make the table really hard to read, also almost all entries in A1 have a lowercase 'a', maybe only label when they differ?; and important differences can be discussed in the manuscript).

- Answer: We agree with this suggestion and removed the statistical analysis from Table A1 (now Table A2).

Figures.

Referee: Some scale modification and additional labels would make the figures easier to read.

Fig. 2.

- *Referee: Matching scales would help the reader (at least 4 groups; a) & c) and b) & d)*

- Answer: We tried this suggestion but it did not improve clarity. Instead, it diminished temporal pattern of the fluxes following fertilization. The reason is because soil N_2O fluxes at F1 (0.3 m from the tree base with incidental fertilization; Figs. 2a and 2b) would be so minimized because of its much lower fluxes than those at F2 (fertilized location; Fig. 2c and 2d). Thus, we kept the original figure.

- *Referee: Add Tree-base distance in the plots to guide the reader*

- Answer: We included these now on the figure panels, in addition to the fact that they were actually included in the figure caption.

- *Referee: Add fertilizer amounts to plot or captions (instead of referring section 2.2)*

- Answer: We included the amount of added N to the caption.

Fig. 3

- *Referee: See comments for figure 2 (y-axis break for a) and b) required)*

- Answer: Please see author's answers for Figure 2 above.

DETAILED COMMENTS

1) Referee: p5, l19: Introduce site abbreviations that you can refer to in the text

Answer: We believe that introducing site abbreviations for the four land uses will not improve clarity but could confuse the reader, since we also used abbreviations for the different chamber locations within the smallholder oil palm plantations (see answer to general comment #3 above).

2) Referee: p5, l22: Introduce H1 and H2 for your hypothesis so you can refer to them in your discussion

Answer: We included this suggestion (see answer to general comment #3).

3) Referee: p6: I would give a site property table here (basically combine A1&A2) and add soil properties – I feel a reference to Allen et 2015 and Hassler 2015 for such fundamental information for the manuscript is not sufficient.

Answer: We gave all the necessary site characteristics, including soil characteristics (pages 6-7, lines 21-1), in section 2.1. Therefore, an additional table for site general characteristics is not necessary (see also our detailed response to comment on Table A1/A2 above).

4) Referee: p6, l16: is the precip data given as SD?

Answer: The precipitation data are the mean of the years 1991-2011 with the standard error among these measurement years.

5) Referee: p6, l20: that is actually substantially higher

Answer: That is true and therefore we highlighted this fact.

6) Referee: p7-8: site & design description could be shortened substantially

Answer: We streamlined section 2.1 by taking out details, mainly regarding the management practices (see answer to general comment #1 above).

7) Referee: p8: Please work on the language in this section: I counted 'was done', 5 times in this paragraph

Answer: After removing lines 6-15, we hope this language shortcomings are also remedied.

8) Referee: p9, l20: give a reference for N fertilizer induced pulse emissions

Answer: We cited Veldkamp and Keller (1997) and Veldkamp et al. (1998) who reported fertilizer-induced pulse emissions (page 9, lines 13-16).

9) Referee: p11: trapezoidal rule should be explained briefly here (esp. since it is not explained in the given reference Hassler at al., 2015, either.; in there is an other reference to Koehler at./ Veldkamp 2013).

Answer: For clarity reasons, we rephrased this sentence. Basically, trapezoidal rule is the simple interpolation between measured fluxes and the interval between sampling days (page 11, lines 16-19).

10) Referee: p12, l4-l10: this is hard to read; just give the equation

Answer: We rewrote these lines into an equation form, aligned to the left margin for ease in reading (page 12, lines 3-6).

11) Referee: p13, l10: "when necessary" – explain

Answer: We improved the sentence; we meant, when assumptions for normal distribution and homogeneity of variance were not met (page 13, lines 14-16).

12) Referee: p13, l13: briefly remember your reader about your hypothesis H1 & H2 here

Answer: We added the hypotheses into the brackets of the sentence (page 13, lines 16-19).

13) Referee: p13, l22- p14, l15: this is very detailed… maybe move this into the appendix/ a supplement?

Answer: We agree with the referee's suggestion and put the detailed statistical description regarding the use of LME models to Appendix A. We revised section 2.3 "Statistical analysis" to describe which comparisons these LME models were applied (pages 13-14, lines 16-1).

14) Referee: p15, l11: mention the reference land uses again

Answer: We included them in brackets (page 15, lines 1 and 7).

15) Referee: p15, l11: "…from soils. In the clay…"

Answer: We take this suggestion (page 15, line 1-2).

16) Referee: p15, l15: Was this systematic? I.e., was there always one measurement (position) an outlier?

Answer: This was not systematic. This occurred in all land uses, where one or two plots in some sampling days displayed higher emissions than the other plots of the same land use within the same landscape.

17) Referee: p16, l3-4: give the fertilizer rates here, too.

Answer: We included them into the brackets (page 15, line 23).

18) Referee: p16, l6: "in the chamber location closest to the tree, soil N2O emissions…"

Answer: We included this suggestion to make clearer which location we are talking about (pages 15-16, lines 25-2).

19) Referee: p16, l9: There is also a peak for site 1 (but smaller)

Answer: That is true! Nevertheless, mean fluxes were statistically not different between chamber location F1 and NF in this site, and hence we only highlighted site 2.

20) Referee: p16, l18: Due to which assumptions? Trees per ha? Avg. basal area of those trees?

Answer: The area-coverage calculation of fertilizer-induced N-oxide emissions was based on the number of trees/hectare. We made this clearer by including this information into the brackets (page 16, lines 13-14).

21) Referee: p18, l3: NH4 (only weak?)

Answer: For NH_4^+, only a weak correlation was found. We stated in section 2.3 (page 14, lines 20-21) that correlations with marginal significant will be included, and this is also clearly identified in Table 3.

22) Referee: p18, l5: What is the temperature amplitude between the measurements? Relatively minor I suppose due to the tropical climate.

Answer: The soil temperatures of the sampling days during 1 yr of measurement in the converted land uses ranged between 24.4 °C and 30.6 °C. This correlation with soil temperature was definitely because of fertilizer-induced high N_2O emissions on one sampling day with relatively high soil temperatures (28.8° C).

23) Referee: p18, l5-9: Remove this single sampling period outright since it clearly seems fertilizer-induced

Answer: We removed these lines and revised Table 3, according to this suggestion, since we also believe that this information is unnecessary.

24) Referee: p18, l13-14: How is this possible?

Answer: NO fluxes following fertilization in chamber location F2 (formerly, chamber b) of the clay Acrisol did not correlate with mineral N contents but instead correlated negatively with WFPS. The clay soil had high water retention capacity and WFPS overshadowed the influenced of mineral N on soil NO fluxes (in a condition with sufficient mineral N availability from fertilization) – soil NO fluxes were favored under conditions of low WFPS. Conversely, in the loam Acrisol, where WFPS were lower than those in the clay Acrisol, and favored for soil NO fluxes, NO was more influenced by mineral N than by WFPS. This is exactly what we discussed in pages 25-26, lines 21-2.

25) Referee: p19, l17: Give the range of your fluxes here for comparison

Answer: The reason why we don’t write in the text the fluxes reported clearly in Table 1 is to avoid redundancy. One clear requirement is that values reported in Tables should never be repeated in the text; instead, we referred to the Table where these values are reflected.

26) Referee: p19, l19-25: This is very wordy, could be shortened substantially

Answer: We need to provide in these sentences the frequency of sampling and spatial replications of the studies to which we compared our values. These are very much needed in order to understand why fluxes from other studies are higher or lower compared to our measured fluxes. Still, we understand the referee's concern and therefore we removed the information on elevation (since we state anyway if we are talking about lowland forests or montane forests) and removed the decimal places but retain the sampling frequency and spatial replication (page 19, lines 10-19).

27) Referee: p20, l8: What about the other literature? You only compare to reports from your specific region

Answer: The reviewer is referring here only the summary statement of our comparisons with other values. We indeed relate our measured fluxes not only with previous studies within Indonesia but also with those studies in other tropical regions. In the first part of this paragraph, we indeed compared our soil N_2O fluxes with values reported in literature (page 19, lines 8-9) and we also put these findings in a broader context (page 20, lines 10-13).

28) Referee: p21, l24: I do not get the reasoning here. Were the fires going on in the region during the measurements?

Answer: Fires are regularly occurring in Jambi region and in the whole of Sumatra Island. During fires, NO levels are generally elevated (Levine, 1999). To highlight this, we included Gaveau et al. (2014), who reported Sumatran fires 2013 (page 21, line 15-16).

29) Referee: p22, l8: Give the observed flux range here for better comparison, also the N application rates would help to judge the observations.

Answer: We did not repeat putting in our measured fluxes in the text as these are clearly stated in Table 1 to which we referred. To minimize the wordiness of our comparison with other reported studies, we removed the information on elevation, but retained the information on replication and sampling frequency. We agree that stating N fertilization rates is important, and we included them if they were provided by the cited studies (pages 21-22, lines 24-18).

30) Referee: p22, l9: Why do you give the elevation here? This is not really a factor (110m, 580,…)

Answer: We took out this aspect (see answer to detailed comment #26).

31) Referee: p22, l12: However the sampling there was very detailed and covered the transition period

Answer: We provided uniformly for all cited studies the frequency of measurement or the duration of measurement, whichever is given by the cited studies, and the replications so that the readers have the full background on how to judge the differences in flux values reported by these studies (see answer to detailed comment #26).

32) Referee: p22, l15: "nine monthly" is a bit deceptive, it's 9 single measurements, right?

Answer: Nine sampling days at monthly interval.

33) Referee: p22: Maybe a literature review table with relevant citations for the investigated land uses combined with your results would be appropriate here? This would also help the better interpret your results in context.

Answer: Yet another table will not shorten this manuscript. Besides there are only few studies that measured soil N_2O fluxes (nothing for soil NO fluxes) from the same land uses to warrant another table. We are convinced that by having incorporated the above mentioned changes (removing information on elevation and rounding off values to have no decimal place) improve this section.

34) Referee: p23, l4-l6: Also true, this seems unnecessary to mention here. Maybe give a half-sentence in the abstract highlighting the novelty of your NO measurements.

Answer: We agree with this comment and have removed this sentence, since we also mention this aspect in the conclusion (page 26, lines 13-15).

35) Referee: p23, l7: remind the reader about the hypothesis again

Answer: We referred back to the hypothesis number, but not rewriting it again in order to avoid redundancy. The reader can easily get back to the hypotheses now that these are referred to in numbers (page 22, lines 19).

36) Referee: p24, l21: Isn't it expected that fertilizer-induced emissions occur at the site where fertilizer is applied?!?

Answer: Yes, of course. But we want to point out here that for banded (meaning around a small area from the tree base) fertilizer application, as was claimed to be practiced by our smallholders, fertilizer-induced N-oxide emissions are limited within the fertilized area and only lasted within a short time. This may be different for large-scale plantations where fertilizers are broadcasted in much larger amounts.

37) Referee: p25, l8: mention your fertilizer rates again for comparison

Answer: We included the rates, as suggested (page 24, line 25).

38) Referee: p25, l9: these seem high; please give the references

Answer: We included the references again: Veldkamp and Keller, 1997; Veldkamp et al., 1998 (page 25, lines 1-2).

39) Referee: p25, l25: pulse application? Maybe: "the event-based application of high N rates" or something similar?

Answer: We agree that this is an awkward wording, and deleted the word "pulse" (page 25, line 18).

40) Referee: p26, l10-12: This is most likely not true for low – medium moisture levels.

Answer: The referee points out that soil NO fluxes do not decrease and soil N_2O fluxes do not increase under low to medium moisture levels. According to Davidson et al. (2000) soil N_2O fluxes start to increase at around 30 % WFPS and soil NO fluxes start to decrease at around 60 % WFPS. WFPS in site 1 of the loam Acrisol soil (chamber locations F1 and F2, which showed a positive correlation between soil N_2O fluxes and WFPS) ranged between 25 and 45 %. WFPS in in site 3 of the clay Acrisol (chamber location F2, which showed a negative correlation between soil NO fluxes and WFPS) ranged between 46 and 68 %. The correlation between N-oxide fluxes and WFPS follows the expected pattern based on the HIP model. Therefore, we are convinced that this sentence is correct.

41) Referee: p26, l12-16: This sentence actually highlights a key problem with such extensive sampling routine and should be discussed further.

Answer: We believed we have indeed discussed this extensively by pointing out the temporal patterns following fertilization at each smallholder site. Besides, an extensive sampling is not a problem but indeed a solution to include the short-term effect of fertilization. It is clear from our results that soil N-oxide measurements should be accompanied with concurrent measurements of known controlling factors; otherwise, investigators will not be able to explain their results. We are indeed able to explain this temporal pattern because we have recognized the simultaneously decreasing WFPS and increasing mineral N content over time in this site 3 of the loam Acrisol soil.

42) Referee: p26, l20: true, although the "full year" is based on few measurements

Answer: We also do not want to overrate our study and therefore clearly stated again, that our measurements were conducted on a monthly basis (page 26, lines 13-14).

43) Referee: p26, l22: Name the hypothesis, the reader might have forgotten which hypothesis was which

Answer: We referred to the hypothesis number (also see answers above for the same comments).

44) Referee: p27, l7: ditto

Answer: Please see answer above.

45) Referee: p27, l12: change unit ‘kg’ to ‘t’

Answer: We changed “kg” to “tons” (page 27, line 6).

REFERENCES

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We thank Dr. Yit Arn Teh for the time he invested to give his thoughtful and constructive comments. For clarity, we have copied his comments and placed our answers below each comment.

GENERAL COMMENTS

Referee: While I am strongly supportive of this work overall, I do have a few concerns. First, I believe that the authors need to reconsider the structure of the Methods and Results sections to improve the clarity of the text. For the Methods section, I was sometimes confused as to which ecosystems/land-use were sampled at what times, and I think the authors should revise the sections describing the experimental design to better clarify the chronology of the measurements. From my reading of the text, it appears that there were 2 parts to this study; the first phase, where gas fluxes were compared among forest, jungle rubber, and small holder plantations. During the second phase, fluxes were compared among small holder and large holder plantations. It would be useful if the text could be edited to make this sampling design a bit clearer.

Answer: We addressed this concern by introducing earlier on (in the abstract, in section 1 “Introduction”, 2.1 “Study area and experimental design” and in section 2.2 **“**Soil N-oxide fluxes and supporting soil factors”) the study coverage, as suggested by Dr. Teh. We now stated in the revised manuscript that there are two parts of the study; the first was on quantifying soil N-oxide fluxes from the four different land-uses (page 7, lines 1-2; page 9, lines 1 and 13), and the second, as a follow-on study, was on the comparison between smallholder and a large-scale oil palm plantations in the loam Acrisol soil (page 2, lines 10-12; page 5, lines 18-21, page 7, lines 11-14; page 9, lines 8-12).

Referee: In addition, measurements were discussed in the Results and Discussion which were not described in the Methods – for example, potential nitrification measurements were performed, but not described in the Methods. By inference, I had assumed that potential denitrification measurements had been conducted too, as the authors later conclude on Page 18, section 3.4 that nitrification was the dominant N-oxide producing process (which implies that other pathways such as denitrification or DNRA were not closely correlated with N-oxide fluxes). I had wondered if these potential nitrification measurements had been conducted as part of another study; if so, then this needs to be acknowledged.

Answer: We mentioned in section 2.3 “Statistical analysis” (page 14, lines 14-18) that we assessed the spatial control of soil biochemical characteristics on annual soil N_2O fluxes, using the soil biochemical data reported in Appendix Table A2; in this table we reported the source of these data.
To improve clarity in our present manuscript, we now mentioned in section 2.2 **“**Soil N-oxide fluxes and supporting soil factors” (page 13, lines 5-9) and section 3.4 “Spatial controls of annual soil N_2O fluxes” (page 18, lines 20-22) the source of these soil biochemical data. We mentioned that these data were reported earlier by Allen et al. (2015) and in our present manuscript we only put in Appendix Table A2 the parameters that showed significant relationships with the annual soil N_2O fluxes.
Furthermore, the entire internal soil-N cycling was quantified in situ (except for denitrification) by Allen et al. (2015), and we used all the parameters of the soil-N cycling to correlate with the annual soil N_2O fluxes. Only the gross nitrification rates showed significantly correlation with annual N_2O

fluxes from the reference land uses across the two landscapes. We did not interpret this correlation as the responsible process for N_2O emission/production in the soil. Instead, we interpreted this as the control of soil N availability on soil N_2O emission/production and gross nitrification as an index of soil N availability. Quantifying the relative importance of nitrification and denitrification on soil N_2O fluxes from these land uses (which cannot be drawn from our data via mere correlation test) is the focus of a follow-on study by our group during the 2nd phase of this project, which has just started this year, 2017.

Referee: Second, I thought that the structure of the Results section could be improved. I felt that the way in which the Results were organised did not convey information clearly about how fluxes varied among land-uses and soil types. In my opinion, I think it would be clearer if the first part of the Results compared trends among land-uses (e.g. forest, jungle rubber, small holders; small holders versus large holders, etc.). The authors could then go on to explore differences among soil types. The second part of the results section could discuss temporal trends in N-oxide fluxes, such as intraannual trends in N-oxide fluxes (if any exist) as well as the pattern in N-oxide fluxes after fertilisation. The last part of the Results could discuss the role of environmental variables and N cycling processes (e.g. nitrification) in regulating flux rates. This could all be achieved without altering the text too much, but simply re-organising how the information is presented.

Answer: Although we understand why the reviewer is suggesting this sequence of flow in the Results, we ask for Dr. Teh's consideration of the basis of our decision on how we had organized the present structure of our results. The main reason of organizing the results this way (N-oxide fluxes 1st from the reference land uses with comparison between the two landscapes and followed by the converted land uses within each landscape, including the smallholder and large-scale oil palm plantations within one landscape, then fertilization effects as the most important management in oil palm plantations, and finally the temporal and spatial controls) is because we need first to establish if from the reference land uses (with no to minimal human disturbance) there are differences between the two landscapes, as baseline data for soil N-oxide fluxes, before going onto the land-use change effect and further onto the controlling factors. This flow of the result presentation also supports the sequence of logic in the discussion section:

a) how our measured fluxes from the baseline reference land uses are comparing with the other findings in the tropics and, with that, establishing how the soil factors control the temporal and spatial patterns of soil N-oxide fluxes.

b) how land-use conversion affected these fluxes and changed the controlling factors, and hence why significant change in N-oxide fluxes was not detected among land uses.

c) finally, the effects of fertilization, and that its importance for improved estimates of annual N-oxide fluxes at a scale larger than our present study lies on the inclusion of large-scale, more intensively fertilized oil palm plantations.

Referee: I had no major concerns about the Introduction and Discussion, as I felt that the authors did an excellent job of framing their research within a wider theoretical and applied *context, and linking their findings back to bigger picture questions about the generic controls on N biogeochemistry in tropical soils.*

Specific comments on individual portions of the text are provided in the section below.

SPECIFIC COMMENTS

1. Referee: Page 5, line 16-page 6, line 9: Generally, I think that this section describing the hypotheses and overall experimental goals is well-written. However, my concern here is how to introduce the second part of the study comparing N gas fluxes in small versus large holder systems in a more intuitive way. The current structure of this section makes the study on small versus large holder systems seem a bit disconnected from the first phase of the work. One possibility might be to introduce this study earlier on in the paragraph, close to the section where the authors pose their hypotheses (which implicitly refer to N availability and the HIP model), as this would then implicitly link-up to ideas about N control on N fluxes, e.g. (my suggestions in the underlined section below):
"We covered four different land uses within two landscapes on highly weathered soils that mainly differed in soil texture (clay and loam Acrisols): forest, rubber trees inter spersed in secondary forest (hereafter called jungle rubber) as the reference land uses, and smallholder rubber and oil palm plantations as the converted land uses. In addi tion, we conducted a follow-on study comparing N gas fluxes across a gradient of N input that encompassed small holder plantations (lower N input rates) a large-scale oil palm plantations (higher N input rates) to try and evaluate the effect of N input rate on N gas fluxes..."

Answer: We greatly appreciate this referee's suggestion and we also see that we should bring out early on the part on the comparison of soil N_2O fluxes between smallholder and large-scale oil palm plantations. We take this suggestion which is now incorporated in page 5, lines 15-21 of the revised manuscript.

2. Referee: Page 7, lines 12-17: In the comparison study between small holder versus large holder systems, were measurements from the small holder systems collected at the same time (i.e. were fluxes from the two types of oil plantations collected concomitantly)? If so, then this should be made clearer in this paragraph.

Answer: No, the measurements between the smallholder and large-scale plantations were not measured concomitantly, mainly because of logistical limitation. The measurement periods were also clearly stated in the original manuscript (page 7, lines 1-8 and lines 11-14; page 9, lines 1-3 and 8-12), and now is clearly shown in Appendix Table A1 (see comment below). This was because our permission to work in the large-scale plantation was settled later than our agreement with the smallholders. However, this time difference in measurement period between these systems is accounted for in the statistical analysis - the linear mixed effect models include measurement period and replicate plot as random effects and only the oil palm plantation type as the fixed effect (Appendix A; page 47, lines 7-14).

3. Referee: Page 9, lines 7-17: It would be useful at the start of this paragraph to remind readers which land-uses were sampled in 2013, 2014 and 2015. Perhaps the authors could put together a table or something similar to represent this information?

Answer: We agree to these suggestions and put the measurement periods in an appendix table (now as Table A1 and the previous Table A1 now Table A2) for quick reference for the readers. We retain in the Methods (as referred to this page by the reviewer) all the description of these measurement periods and only give reference to Table A1 for summary.

4. Referee: Page 9, lines 18-20: Were the authors able to determine if N_2O fluxes varied with distance from palms? Given the spatial structure in oil palm plantations, and the potential effects of roots and fertiliser application, it would be useful to know if the data could be corrected for spatial effects (if they exist) caused by proximity to palms.

Answer: The spatial structures of oil palms that are commonly seen in large-scale plantations are not consistent in smallholder plantations. The smallholder farmers also don’t have regular spots for fertilizer applications, as we have explained in the manuscript based on our results. The deployment of the 4 permanently installed chamber bases per replicate plot is described in detail in section 2.1 “experimental design”, page 7, lines 1-7. These chambers had random spatial locations in order to represent each replicate plot. These randomly placed chambers happened to be within 1.8 – 5-m distance to the palms and we conducted a Spearman’s rank correlation test between N-oxide fluxes and distance to palms of the four replicate plots (sites) within each landscape. There were no significant correlations (P = 0.84–0.94). Thus, there was no basis for correction for any spatial effect as there exist no relationship with distance to the palms.

The best way to quantify any possible effects of fertilization is the way we described in our study, assuming that the random placement of chambers and the monthly sampling may have missed the fertilized spots and short-term effects of N application. Hence, we did the more intensive measurements following fertilization in the same smallholder plantations (using the same rate and application methods the smallholders claimed to employ) in order to quantify the contribution of fertilization, both in terms of space and duration, on our annual estimates.

5. Referee: Page 15, lines 16-25: I wonder if the large variation in the mean fluxes is driven by a high degree of within-plot spatial variability, which might linked to where fertiliser is applied, the distribution of palms, or surface residues (e.g. palm fronds or planted understory plants)? Is it possible to determine to what extent micro-scale variability, linked to spatial structure in the plantation, was causing variance in the measurements? This could help in interpreting the data, and understanding differences linked to management differences in small holder vs larger holder systems.

Answer: This question is related to our answer in #4 above. Fig. 1 shows the mean and SE from the 4 sites per land use on each sampling day. This variation, i.e. SE, on each sampling day reflected the variability among the 4 sites. The SE did not reflect within-plot variation because in the stat analysis (LME) the mean of the 4 chambers per plot (as subsamples nested within plot) on each sampling day is the value used in the LME analysis, which is conducted across all sampling days with land use as fixed effect and plot and sampling day as random effects (Appendix A, page 47, lines 2-3 and 6-7). Similarly, the statistically undetectable difference between the large-scale and smallholder oil palm plantations was also due to the large spatial variability among the 4 replicate plots and not by micro-scale variability within each plot. We have ascertained this in this large-scale plantation by statistical analysis since we have placed the 3 chambers/plot systematically to characterize any possible micro-scale variability within plots. In this large-scale plantation, we placed the 3 chambers/replicate plot such that the 1st chamber was on the fertilized band (at 0.8-1-m distance to the palm base) and the next 2 chambers were placed at a succeeding 2-m distance from each other. These 3 chamber locations, however, did not differ ($P = 0.70$) in soil N_2O fluxes across the measurement period. This was due to the fact that the management practices were not consistently done as claimed by the plantation managers and smallholders. The field workers had sometimes broadcasted the fertilizers, sometimes also just applied in a band around the palm (page 8, lines 13-20), and sometimes piled the cut fronds in one row and sometimes in another row or sometimes not at all. The area and duration of effects of 1-2 times/yr fertilizer application in smallholders (which had 2-4 times lower application rates than in large-scale plantations) were small and only lasted for a few days (Figs. 2 & 3). We allocated full subsections of these effects in the Results and Discussion.

Even if we do a variance component analysis of the soil N_2O fluxes, to partition the scales' contributions to the overall variance, this will not answer whether the within-plot variability is related to spatial structure of the management practices within plots. Variance component analysis will only quantify how much of the overall variability is accounted by within-plot variation. We think that the spatial structure of the management practices will only be detectable if there was a consistent management practices, e.g. when experimental plots are controlled by researchers. As we all know, smallholders as well as the large-scale plantations in reality do not have a uniform management practices in all years in terms of where fertilizers and residues are exactly placed, and hence we were unable to detect any statistically significant relationship of within-plot pattern of soil N_2O fluxes with what is supposed-to-be the spatial structure management practices. That is however what was occurring in our actual field conditions. As we also did not find in the large-scale plantation correlation or differences in soil N_2O fluxes between chamber locations and distance to palms, we also cannot relate within-plot variability to the spatial structure of this plantation. This is the main reason why we focused instead on our more frequent measurement following our own fertilization (mimicking farmers' claimed practice) to quantify the spatial and temporal contributions of fertilization on soil N_2O fluxes (Fig. 2 & 3).

6. Referee: Page 16, lines 1-10: There is a potential confounding effect here due to the presence of roots which needs to be acknowledged. Granted, it is likely that the effect of fertiliser application will overwhelm the effect of roots in the immediate to short-term after fertilisation. However, it is worthwhile knowing whether or not the presence of roots ameliorates the effects of fertiliser (e.g. plant competition with nitrifiers/denitrifiers for inorganic N may reduce the relative gases loss of N in areas with high root densities). For example, do the authors have data on N gas fluxes from root-free and rhizosphere soil in the large holder systems to compare against? My thought here is that if the N *application rate is higher in the large holder systems it may be possible to compare N fluxes from rhizosphere soil with different N application rates to evaluate the effect of N input rate on gas fluxes (i.e. making a like-for-like comparison).*

Answer: From another study (conducted by another group in this collaborative project) that measured root distribution in the same smallholder oil palm plantations, there were no significant correlations between root mass distribution with distance to palms. This was attributed to the facts that these are mature plantations (12-16 yrs old, except one site that was 9 yrs old) and the weeding practices in smallholder plantations were not intensive (1-2 times per year only; Hassler et al., 2015) and hence the ground was almost always covered with undergrowth. It is impossible to see a root-free area. We don't think root can ameliorate the pulse effects of N fertilization on soil N_2O fluxes (the total flux was also only 0.2-0.7% of the added N; page 17, lines 14-16), because we would have not seen a similar effect in tropical forest soils all covered with roots (e.g. Koehler et al. 2009). In this latter study, soil N_2O emissions clearly increase following N fertilization (at comparable application rate as we have in the present study) and went back to the background levels after about 6 weeks (during which the added N are already recycling within the soil N cycle). In the large-scale oil palm plantation PTPN VI (which was 12 yrs old), we don't have root data. Following Dr. Teh's suggestion of like-for-like comparisons, we conducted statistical analysis between the large-scale and smallholder plantations considering only the chambers on fertilized spots (the supposed-to-be spots which the smallholders and PNPT VI manager claimed where fertilizer was banded or broadcasted) and the sampling days within 6 weeks following fertilization; and a separate analysis for sampling days after six weeks of fertilization for chambers on locations which were not supposed-to-be fertilized. There was still no detectable significant difference between the large-scale and smallholder plantations (P = 0.50-0.67). Thus, the argument on confounding effect of roots was not convincing, at least from our dataset. The short-term effects of fertilizer application clearly showed the overwhelming effects (Figs. 2 & 3), although the emission percentage to amount of N added was actually only small; thus, presumably a large part of the added N must have been incorporated into the soil N cycle and eventually into the plant-soil cycling.

7. Referee: Page 16, lines 1-17: Regarding the use of locations a, b and c to refer to different distances to the palm; perhaps it may be possible to use identifiers that are a bit more descriptive, as this would make it easier for the readers to pick-up on the information quickly? e.g. 0.3 m = "inner root ball", 0.8 m = "outer root ball", 4-4.5 m = "inter-palm space" (or something similar)? Use of letters is a bit more abstract and (while clear) forces the reader to refer back to the tables or legends to remind themselves of the meaning of these abbreviations. Also – where trends are statistically significant, the authors could list the P-values from the multiple comparisons tests in parentheses to highlight where significant trends existed (I see that this has been done for the table, but would be useful for the reader if this was stated in the text, too).

Answer: We agree with the suggestion to use meaningful identifiers rather than a, b and c. To address this concern, we followed the suggestion of referee 1 and introduced the following clearer abbreviations: F1 = chamber location with incidental fertilization (0.3 m from the tree base), F2 =

fertilized chamber location (0.8 m from the tree base), NF = non-fertilized chamber location (4-4.5 m from the tree base) (page 10, lines 5-10 and Tables 2 & 4).

Furthermore, we indeed gave consistently the P values of all comparisons in the text and not just in the Table) (i.e. 1st and 3rd paragraphs in section 3.2 for comparisons among chambers).

8. Referee: Page 16, lines 18-22: Are these estimates derived from the trapezoidal extrapolations or some form of area-weighted upscaling?

Answer: The calculations for these estimates were explained in the Methods, pages 11-12, lines 20-6. From this equation, the total N-oxide emissions following fertilization (chambers F1 & F2) and the background fluxes (from the unfertilized chamber NF) are the trapezoidal calculations of the fluxes shown in Figs. 2 & 3 for each site/replicate plot. Since fertilizer-induced fluxes were limited in space and time, we also considered the fertilized area (multiplied by the tree density/ha) and the frequency of fertilizer application.

9. Referee: Page 18, section heading 3.3 Temporal controls of soil N-oxide fluxes: This section appears to discuss the relationship between environmental variables/drivers and N gas fluxes. Perhaps it may be more appropriate to re-name this section as "Role of abiotic variables in controlling N-oxide fluxes"? Or, if the authors may wish to more explicitly discuss how temporal variability in these environmental drivers contribute to fluctuations in N-oxide fluxes?

Answer: This page is still in the Result section – we mainly present (not discuss) the controlling factors of the temporal pattern of soil N-oxide fluxes. We keep this section heading, because we explicitly want to distinguish between temporal and spatial (section 3.4.) (and both sections considered abiotic factors) controls of N-oxide fluxes.

10. Referee: Page 18, section heading 3.4 Spatial controls of annual soil N2O fluxes: Similar to my above point (9), I do not feel that this heading properly describes what is discussed in the section. In this section, the authors discuss the relationship between N cycling processes rates and N-oxide fluxes, in order to evaluate the principal source of N oxides in these soils. They conclude that nitrification is probably the dominant driver of N-oxide fluxes because of the correlation between nitrification rates and gas fluxes. Perhaps the section could be retitled "Role of different N cycling processes in regulating N-oxide fluxes"? Also – I re-read the Methods and did not see the nitrification potential experiments described. Was this work done as part of another study or was this done as part of this work? In either case, this needs to be added to the Methods to make it clear that this work was done as the reference to nitrification (although interesting and relevant) came as a but of a surprise.

Answer: We have explicitly explained in the statistical analysis (page 14, lines 14-18) that for assessing the spatial controls of soil N_2O fluxes, we used the annual flux per plot (and thus excluding the temporal variation) and conducted the correlation analysis with all the measured soil factors (physical and biochemical factors as well as the soil-N cycling processes) across the landscapes, encompassing soil conditions of the plots within the reference land uses and within the converted land uses. Thus, any significant relationships we observed suggested the range of conditions across plots and hence indicated the spatial controls. We also now added in the Methods (see answer to general comment #2 above) the descriptions of the sources of these soil controlling factors that were included in these correlation analysis for section 3.4. The control of gross nitrification was not interpreted as the main source of N_2O fluxes in these soils but rather as an indicator of N availability in the soil; please see our answer to this similar comment in the 2nd general comment above.

11. Referee: Page 20, lines 9-22: Fluxes of NO from these systems, particularly oil palm, is extremely novel and of wider environmental significance, given the potential role of NO in tropospheric ozone formation, N deposition, and regional atmospheric oxidant (OH) balance. It would be useful in the discussion if the authors could bring into the discussion some of the findings from earlier atmospheric sampling campaigns by the OP3 consortium (Fowler et al., 2011, Hewitt et al., 2009), where elevated NOx concentrations were found in the troposphere near oil palm plantations? Hewitt et al. (2009) and Fowler et al. (2011) suggest that the implications of enhanced NO emission from oil palm could be potentially regionally significant, and the work here in Sumatra on ground-based NO fluxes would be an interesting counter-point to the atmospheric sampling work from Sabah.

Answer: We very much appreciated this suggestion and included this aspect in section 4.2 "Land-use change effects on soil N_2O and NO fluxes from oil palm plantations" (page 23, lines 17-23).

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Soil nitrogen oxide fluxes from lowland forests converted to smallholder rubber and oil palm plantations in Sumatra, Indonesia

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Abstract. Oil palm and rubber plantations cover large areas of former rainforest in Sumatra, Indonesia, supplying the global demand for these crops. Although forest conversion is known to influence soil nitrous oxide (N_2O) and nitric oxide (NO) fluxes, measurements from oil palm and rubber plantations are scarce (for N_2O) or nonexistent (for NO). Our study aimed to (1) quantify changes in soil-atmosphere fluxes of N-oxides with forest conversion to rubber and oil palm plantations, and (2) determine their controlling factors. In Jambi, Sumatra, we selected two landscapes that mainly differed in texture but both on heavily weathered soils: loam and clay Acrisol soils. Within each landscape, we investigated lowland forest, rubber trees interspersed in secondary forest (termed as *jungle rubber*), both as reference land uses, and smallholder rubber and oil palm plantations, as converted land uses. In the loam Acrisol landscape, we conducted a follow-on study in a large-scale oil palm plantation for comparison of soil N_2O fluxes with smallholder oil palm plantations. Land-use conversion to smallholder plantations had no effect on soil N-oxide fluxes (P = 0.58 to 0.76) due to the generally low soil N availability in the reference land uses that further decreased with land-use conversion. Soil N_2O fluxes from the large-scale oil palm plantation did not differ with those from smallholder plantations (P = 0.15). Over one-year measurements, the temporal patterns of soil N-oxide fluxes were influenced by soil mineral N and water contents. Across landscapes, annual soil N_2O emissions were controlled by gross nitrification and sand content, which also suggest the influence of soil N and water availability. Soil N_2O fluxes (μg N m^{-2} h^{-1}) were: 7 ± 2 to 14 ± 7 (reference land uses), 6 ± 3 to 9 ± 2 (rubber), 12 ± 3 to 12 ± 6 (smallholder oil palm), and 42 ± 24 (large-scale oil palm). Soil NO fluxes (μg N m^{-2} h^{-1}) were: -0.6 ± 0.7 to 5.7 ± 5.8 (reference land uses), -1.2 ± 0.5 to -1.0 ± 0.2 (rubber) and -0.2 ± 1.2 to 0.7 ± 0.7 (smallholder oil palm). To improve estimate of soil N-oxide fluxes from oil palm plantations in this region, studies should focus on large-scale plantations (which usually have two to four

times higher N fertilization rates than smallholders) with frequent measurements following fertilizer application.

1 Introduction

Expansion of industrial forestry and agriculture has caused rapid deforestation in Sumatra, Indonesia, resulting in a total primary forest loss of 36 % between 1990 and 2010 (Margono et al., 2012). Nowadays, most accessible lowland rainforests have been converted (Laumonier et al., 2010) into economically important crops, such as oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*), with an area of 9.2 million hectare (Mha) (BPS, 2016a). Indonesia is currently the principal oil palm producer and second largest rubber producer worldwide (FAO, 2016), and Sumatra is the most important contributor to the Indonesian production (BPS, 2016b). Despite the extent of land-use change in Sumatra, it is still uncertain how forest conversion will affect soil emissions of climate-relevant N-oxide gases, nitrous oxide (N_2O) and nitric oxide (NO). Only a few studies so far have reported soil N_2O fluxes from forest conversion to these rapidly increasing and economically important land uses, oil palm and rubber, on lowland mineral soils in Southeast Asia (Aini et al., 2015; Ishizuka et al., 2002, 2005; Yashiro et al., 2008) and no study exists on soil NO fluxes.

Tropical forest soils are major sources of N_2O and NO, emitting 1.3 Tg N_2O-N yr^{-1} (Werner et al., 2007) and 1.3 Tg NO-N yr^{-1} (Davidson and Kingerlee, 1997) to the atmosphere, whereby considerable amounts of NO are expected to get redirected in forest systems since NO is easily oxidized to NO_2 which, in turn, is absorbed by leaves (Jacob and Bakwin, 1991; Sparks et al., 2001). N_2O is a potent greenhouse gas (IPCC, 2013) and is projected to be the single most important ozone-depleting substance throughout the 21st century (Ravishankara et al., 2009). NO plays an important role in the formation of tropospheric ozone, which in itself is an important greenhouse gas (Lammel and Graßl, 1995). N_2O and NO are produced in soil by the microbial processes of nitrification and denitrification. The conceptual model of “hole-in-the-pipe” (HIP), which had been validated by studies in the tropics (Davidson et al., 2000), suggests that production and consumption of these gases in soils are influenced by two levels of control: first, the amount of soil available N, and second, the soil water content. HIP suggests that the higher the soil N availability, the higher are the soil N-oxide fluxes, and that well-aerated soil conditions (low moisture contents) favor for nitrification with NO as the main gaseous product while with increasing water content denitrification with increasing proportion of N_2O prevails (Davidson et al., 2000). Although there are other factors affecting soil N_2O and NO fluxes through their influence on nitrification and denitrification (e.g., soil pH, temperature, bioavailable carbon; Firestone and Davidson, 1989; Heinen, 2006; Skiba and Smith, 2000), landscape-scale investigations in tropical areas show the dominant role of soil N availability and water content (Corre et al., 2014; Koehler et al., 2009; Müller et al., 2015).

Conversion of tropical forests to agricultural land uses generally alters soil N-oxide fluxes through their effects on soil N availability and aeration as a consequence of management practices (e.g., fertilization, harvest, cultivation), which can add and export nutrients as well as compact or loosen the soil (Keller and Reiners, 1994; Veldkamp et al., 2008). In particular, the application of N-containing fertilizers can increase N-oxide emissions (Matson et al., 1996; Veldkamp et al., 1998) whereas agricultural land uses without fertilizer application lead to long-term reductions of soil N-oxide fluxes or to comparably low-level fluxes as those from previous forests (Ishizuka et al., 2005; Keller and Reiners, 1994; Verchot et al., 1999). In tropical regions, it has been shown that soil NO and N_2O emissions can be very high following fertilizer application, constituting 6.4–8.6 % of applied N fertilizer especially at high fertilizer application rates (Veldkamp and Keller, 1997; Veldkamp et al., 1998).

For lowland forests on highly weathered soils in Sumatra, Indonesia, where our present study was conducted, it has been shown that soil N availability (with gross rates of ammonium (NH_4^+) transformations as indices) is higher in the clay than loam Acrisol soils (Allen et al., 2015), suggesting that soil texture controls soil fertility which in turn affects plant productivity, soil water holding capacity, decomposition and ultimately soil-N cycling (Allen et al., 2015). Conversion of lowland forest and jungle rubber to oil palm and rubber on these Acrisol soils showed intermediate soil N availability in oil palm plantations, due to abatement of soil fertility decline by low to moderate applications of fertilizers and lime, whereas the unfertilized rubber plantations displayed the lowest soil N availability and fertility in general (Allen et al., 2015).

Our present study focuses on soil N_2O and NO fluxes from a region in Jambi, Sumatra where increased deforestation for rubber and oil palm production has occurred in the last two decades. We covered four land uses within two landscapes on highly weathered soils that mainly differed in soil texture (clay and loam Acrisols): forest, rubber trees interspersed in secondary forest (hereafter, termed as jungle rubber) as the reference land uses, and smallholder rubber and oil palm plantations as the converted land uses. In addition, we conducted a follow-on study to evaluate the effect of N input rate on soil N_2O fluxes by comparing a large-scale (with 2–4 times higher fertilization rate) and smallholder plantations within the same landscape of the loam Acrisol soil. Based on the above mentioned findings on soil N availability, we formulated two hypotheses: (H1) soil N_2O and NO fluxes from the reference land uses will be higher in the clay than the loam Acrisol landscapes; and (H2) forest and jungle rubber will have the highest soil N_2O and NO fluxes, followed by the smallholder oil palm plantations (fertilized at low to moderate rates), and with the lowest fluxes from the unfertilized rubber plantations. Our study aimed to (1) quantify changes in soil-atmosphere fluxes of N-oxides with forest conversion to smallholder oil palm and rubber plantations, (2) determine the temporal controls of soil N-oxide fluxes measured within one year, and (3) assess landscape-scale controlling factors of annual soil N_2O fluxes from converted lowland landscapes in Sumatra, Indonesia. Our study contributes to the much needed information on soil N-oxide fluxes from these economically and globally relevant tropical land uses.

2 Material and methods

2.1 Study area, experimental design and management practices

The study region is situated in Jambi province, Sumatra, Indonesia (2° 0’ 57” S, 103° 15’ 33” E, and elevation of 73 ± 3 m above sea level), where conversion of forest to rubber and oil palm plantations is widespread. The area has a mean annual temperature of 26.7 ± 0.1 °C and a mean annual precipitation of 2235 ± 381 mm (1991–2011; data from a climatological station at the Jambi Sultan Thaha Airport). During our study year (2013), annual rainfall in the study region was 3418-3475 mm (data from climatological stations at the Harapan Forest Reserve, Sarolangun and Lubuk Kepayang, approximately 10–20 km from our sites), which were higher than the long term average. Total dissolved N deposition via rainfall was between 12.9 ± 0.1 and 16.4 ± 2.6 kg N ha^{-1} yr^{-1}, measured at two locations in the study region during 2013 (Kurniawan, 2016).

We delineated the study region in two landscapes, which have the same highly weathered soil group but mainly differed in soil texture: clay and loam Acrisol soils. The clay Acrisol soil had larger pH (4.5 ± 0.0), base saturation (23 ± 6 %) and Bray-extractable P (1.4 ± 0.1 g P m^{-2}) and lower Al saturation (61 ± 3 %) in the top 10 cm depth compared to the loam Acrisol soil (4.3 ± 0.0 pH, 11 ± 1 % base saturation, 0.5 ± 0.1 g P m^{-2} and 80 ± 1 % Al saturation) (all $P \leq 0.05$; Allen et al., 2015). In the first part of our study, we investigated four land-use types within each landscape: lowland forest, jungle rubber, both as the reference land uses, and smallholder monoculture plantations of rubber and oil palm, as the converted land uses. Each land use within each landscape had four sites as replicates, and we laid out a 50 m × 50 m plot in each replicate site; in total we had 32 plots. Within each plot, a 10 × 10 grid was established and we randomly selected four subplots (5 m × 5 m each) per plot, each with one permanently installed chamber base for measurements of soil N-oxide fluxes. All measurements (see Sect. 2.2) were conducted in 2013 (Appendix Table A1). A more detailed description of the study sites and plot design was reported earlier by Allen et al. (2015) and Hassler et al. (2015).

The second part was a follow-on study, wherein we conducted additional measurements in a large-scale oil palm plantation (called PTPN VI) in the loam Acrisol landscape from 2014 to 2015 in order to compare with the smallholder oil palm plantations within the same landscape (Appendix Table A1). In the PTPN VI site, we selected four replicates at a distance of 50 m apart. At each replicate, we installed three permanent chamber bases at 0.8 m, 2.8 m and 4.8 m from the tree base, in order to characterize possible spatial variation caused by management practices within each replicate.

Based on our interviews with the smallholders, the monoculture plantations were established after clearing and burning of either forest or jungle rubber and hence these land uses served as the reference land uses with which the converted plantations were compared. Additionally, the comparability of initial soil conditions between the reference and converted land uses was tested based on a land use-independent soil characteristic, i.e., clay content at 0.5–2 m depth, which did not statistically differ among land uses within each landscape (Allen et al., 2015; Hassler et al., 2015). Thus, changes in soil N-oxide fluxes can be attributed to land-use change with its associated management practices. The plantations' ages ranged between 7 and 17 years, and tree density, tree height, basal area and tree species abundance were higher in the reference land uses than the monoculture plantations (all reported by Allen et al., 2015; Hassler et al., 2015; Kotowska et al., 2015).

Management practices in the plantations included manual harvest, weeding and fertilizer application (details reported by Hassler et al., 2015). In 2013, fertilization in the smallholder oil palm plantations was conducted 1–2 times per year and fertilization rates ranged between 48–88 kg N ha^{-1} yr^{-1} (except two smallholders who applied 138 kg N ha^{-1} yr^{-1}), 21–38 kg P ha^{-1} yr^{-1} and 40–157 kg K ha^{-1} yr^{-1}, with the lower range in the clay Acrisol and the upper range in the loam Acrisol. The fertilizer sources were NPK complete, urea and KCl. One of the smallholders in the loam Acrisol landscape applied 200 kg dolomite ha^{-1} yr^{-1}. Fertilizers were applied around each palm tree at about 0.8–1 m from the stem base (Hassler et al., 2015). Rubber plantations were not fertilized. In the large-scale oil palm plantation PTPN VI, fertilizer application rates were typically higher than those in smallholder plantations; fertilizers were applied once in 2014 at the rates of 196-36-206 kg N, P, K ha^{-1} yr^{-1}, with also 602 kg dolomite ha^{-1} yr^{-1}, and once before the end of our measurements in July 2015 at the rates of 96-23-96 kg N, P, K ha^{-1} yr^{-1}. The fertilizer forms were NPK complete, urea, triple superphosphate and KCl. Application in this large-scale plantation was done partly manually by applying the fertilizers at 1-m distance to the tree base, and partly mechanically by broadcasting the fertilizer within 1–3 m distance from the palm rows. In 2015, fertilizers were mainly mechanically broadcasted within these inter-rows.

2.2 Soil N-oxide fluxes and supporting soil factors

In the first part of our study, soil N_2O fluxes were measured in all land uses (32 plots) at monthly interval from December 2012 to December 2013, whereas soil NO fluxes were measured four times between March and September 2013 (Appendix Table A1). Two forest sites and one jungle rubber site in the clay Acrisol landscape were not measured for soil NO fluxes due to difficulty in accessing these sites that did not allow us to stabilize the NO detector during transport in the field (i.e., using motorcycle on very rugged trails). Soil NO fluxes were not measured as frequently as N_2O fluxes because these fluxes were always very low at all sites and we decided to stop this measurement in September 2013. In the follow-on study, soil N_2O fluxes were measured more frequently (biweekly from July 2014 to July 2015; Appendix Table A1) in a large-scale oil palm plantation PTPN VI (in congruent with its high fertilizer application rate) to compare with the smallholder oil palm plantations within the same landscape of the loam Acrisol soil.

For the first part of our study, we used randomly installed chamber bases (with distances to the tree base between 1.8 and 5 m; see Sect. 2.1) with monthly measurements, which may have missed the N fertilizer-induced pulse of soil N-oxide emissions in the smallholder oil palm plantations (Veldkamp and Keller, 1997; Veldkamp et al., 1998). Therefore, we conducted more intensive measurements of soil N_2O fluxes during 3 to 8.5 weeks (with 6 to 11 sampling days) following fertilizer application at three of the smallholder oil palm plantations within each landscape. These measurements served to characterize the short-term, N fertilizer-induced contribution (e.g., Koehler et al., 2009) to total N_2O fluxes. Soil NO fluxes were also measured during 6 to 8.5 weeks (with 9 to 10 sampling days) following fertilizer application at one of the smallholder oil palm plantations within each landscape. Measurements in the three smallholder oil palm plantations at each landscape were conducted during October–December 2013, January–March 2014, and February–April 2014 (Appendix Table A1). We applied the same fertilizer forms, rates and methods as used by the smallholders. Three oil palm trees were selected in each of the six sites. In the clay Acrisol landscape, each tree was applied with 2 kg complete NPK fertilizer (equivalent to 0.32 kg N tree^{-1}), whereas in the loam Acrisol, each tree was applied with 2 kg of combined complete NPK, ammonium sulfate and KCl fertilizers (equivalent to 0.26 kg N tree^{-1}). The fertilizer was applied within 0.8–1 m distance from the tree base. We installed three permanent chamber bases at various distances from the tree base: 0.3 m from the tree base (F1 = chamber location with incidental fertilization), 0.8 m from the tree base that was on the fertilized area (F2 = fertilized chamber location), and 4–4.5 m from the tree base that was in the middle of the inter-rows and served as the reference chamber without fertilizer application (NF = non-fertilized chamber location).

Soil N_2O fluxes were measured using the same methods employed in our earlier studies (e.g., Corre et al., 2014; Koehler et al., 2009). During gas sampling, the permanently installed chamber bases were covered with vented static, polyethylene hoods (chamber area of 0.05 m^2 and total volume of 12 L), and four gas samples (30 mL each) were taken at 1, 11, 21 and 31 min after chamber closure by connecting a syringe with a Luer-lock to the chamber sampling port. Gas samples were immediately injected into pre-evacuated 12 mL Labco Exetainers sealed with rubber septa (Labco Limited, Lampeter, UK), maintaining an overpressure; these exetainers have been tested by our group to be leak proof during extended period of storage (e.g., up to 6 months) (Hassler et al., 2015). Within 3–4 months the gas samples were transported by airfreight to Germany and were analyzed upon arrival using a gas chromatograph with an electron capture detector (GC 6000 Vega Series 2, Carlo Erba Instruments, Milan, Italy). For the measurements from March–July 2015 in the large-scale oil palm plantation PTPN VI, the gas samples were analyzed with another gas chromatograph (SRI 8610C, SRI Instruments Europe GmbH, Bad Honnef, Germany), which had been previously cross-calibrated using the same standards. For calibration, three standard gases were used with concentrations of 360, 1000 and 1600 ppb N_2O (Deuste Steininger GmbH, Mühlhausen, Germany).

Soil NO fluxes were measured (described in detail in our earlier works, e.g., Corre et al., 2014; Koehler et al., 2009) using the same chamber bases described above. During measurements, the chamber bases were covered with dynamic vented, polyethylene hoods (total volume of 12 L), and NO concentrations were measured in situ during 5–7 min following chamber closure using a Scintrex LMA-3 chemiluminescence detector (Scintrex, Ontario, Canada), in which NO is oxidized to NO_2 by a CrO_3 catalyst after which it reacts with a luminol solution. Calibration of the NO detector was carried out at each site prior to and after measurements using a two-point calibration of a standard gas with 3000 ppb NO (Deuste Steininger GmbH, Mühlhausen, Germany) which was diluted using dried ambient air. NO measurements were recorded every 5 seconds using a data logger (CR510, Campbell Scientific, Logan, USA).

Soil N_2O and NO fluxes were calculated from the linear increase of concentration over time of chamber closure and adjusted for air temperature and atmospheric pressure, measured at each site on each sampling day. Annual soil N_2O fluxes from the monthly sampling at each site were estimated using the trapezoidal rule, which is an interpolation between measured fluxes and the interval between sampling days. Interpolated fluxes were summed for the entire year (e.g., Hassler et al., 2015). Annual NO fluxes were not calculated, since we only conducted four measurement periods for each plot as explained above. To calculate the N fertilizer-induced pulse of soil N-oxide fluxes, we also used the trapezoidal rule on day intervals between measured flux rates to estimate the total flux during the entire period following fertilizer application, covering pre-fertilizer level, the peak, and the return to background levels of soil N-oxide fluxes. We calculated the percentage of combined soil NO and N_2O emissions from the applied N-fertilizer rate at each site as follows:

% NO-N + N_2O-N of N applied yr^{-1} = (NO-N + N_2O-N fluxes from F1 and F2 chambers – NO-N + N_2O-N fluxes from NF chamber) * frequency of fertilization yr^{-1} * fertilized area (m^2 ha^{-1}) ÷ N fertilization rate (kg N ha^{-1} yr^{-1}* 10^9 µg/kg) * 100

where NO-N + N_2O-N is expressed in µg N m^{-2} for the entire period of fertilizer effect. In this calculation, we included fluxes from chamber location F1 in order to include any incidental fertilizer application to this area (possibly from previous applications by the smallholders and possible redistribution of applied nutrients within the soil), since N-oxide fluxes from chamber location F1 were often higher than those from NF chambers (see Sect. 3.2).

Soil factors known to control soil N-oxide fluxes (i.e., temperature, water-filled pore space (WFPS), and extractable NH_4^+ and nitrate (NO_3^-) were measured within the top 0.05 m depth during each soil N-oxide flux measurement at all 32 sites and at the six sites of smallholder oil palm plantations following fertilization. Soil temperature was measured close to each chamber base using a digital thermometer. Soil samples were taken at 1 m distance from the four chambers, pooled, mixed thoroughly, and subsampled for immediate extraction of mineral N in the field, using prepared extraction bottles containing 150 mL 0.5 M K_2SO_4. Upon arrival at the field station, extraction bottles were shaken for 1 h, filtered and extracts were frozen immediately. The remaining soil sample was used to determine the gravimetric moisture content (by oven-drying for at least 1 day at 105 °C), whereby WFPS was calculated using a particle density of 2.65 g cm^{-3} for mineral soil and the measured soil bulk density at our study sites (Allen et al., 2015). Concurrent to the measurements following the fertilizer applications, soil was sampled close to each of the chamber locations F1, F2 and NF (described above) and was processed separately for mineral N extraction and WFPS determination. Frozen extracts were transported by airfreight to Germany and analyzed for NH_4^+ and NO_3^- concentrations using continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstedt, Germany), as described in detail by Hassler et al. (2015).

In addition, soil physical and biochemical parameters within the top 0.1 m were measured once in 2013 at all 32 plots (i.e. soil-N cycling processes, including gross nitrification as one of the indices of N availability in the soil, microbial biomass, total organic C, total N, exchangeable cations, pH, soil texture and soil bulk density), reported by Allen et al. (2015). We used these soil parameters to analyze their relationships (see Sect. 2.3) with annual soil N_2O fluxes and reported the parameters that showed significant relationships with annual soil N_2O fluxes in Appendix Table A2.

2.3 Statistical analysis

We first tested each parameter for normal distribution (Shapiro-Wilk's test) and equality of variance (Levene's test), and a logarithmic transformation was applied when these assumptions were not met. Linear mixed-effect (LME) models (Crawley, 2007) were used to assess differences in N-oxide fluxes between landscapes for the reference land uses (testing H1) or to assess differences in N-oxide fluxes among land uses within each landscape (testing H2). Furthermore, a LME model was applied to assess differences in soil N_2O fluxes between the smallholder and large-scale (PTPN VI) oil palm plantations (as a follow-on study) within the loam Acrisol landscape. The LME models were also used to asses fertilization effects (i.e., as represented by the chamber locations F1, F2 and NF) on soil N-oxide fluxes from smallholder oil palm plantations and to test differences in N-oxide fluxes between landscapes following fertilization for chamber locations F1 and F2. The detailed descriptions of the LME models are provided in Appendix A. Significant differences were based on the analysis of variance with Fisher's least significant difference test for multiple comparisons. We set the statistical significance at $P \leq 0.05$ and, only for a few specified parameters, we also considered marginal significance at $P \leq 0.09$ because our experimental design encompassed the inherently high spatial variability in our study area (e.g., Hassler et al., 2015).

To assess the temporal relationships between soil N-oxide fluxes and soil factors (temperature, WFPS, NO_3^- and NH_4^+), we used the means of the replicate plots per land use on each of the 12 monthly measurements and conducted Pearson's correlation test separately for the reference land uses (forest and jungle rubber, $n = 48$ (N_2O), $n = 16$ (NO)) and the converted land uses (rubber and oil palm, $n = 48$, (N_2O), $n = 16$ (NO)) across landscapes for the whole year. Similarly, for soil N_2O and NO fluxes following fertilizer application from smallholder oil palm plantations, we used the means of the three replicate trees per chamber location on each sampling day and conducted Pearson's correlation test for each site across the entire measurement period of fertilization effects ($n = 6$–11). To assess the spatial controls of soil biochemical characteristics (Appendix Table A2) on annual soil N_2O fluxes, we used the annual flux of each replicate plot and conducted Spearman's rank correlation test separately for the reference land uses and converted land uses across landscapes ($n = 16$) and within each landscape ($n = 8$). We did not assess the spatial control of soil biochemical characteristics on annual soil NO fluxes since we did not calculate annual flux from the four measurement periods (as explained in Sect. 2.2). Correlations were considered statistically significant at $P \leq 0.05$ and marginally significant at $P \leq 0.09$. All statistical analyses were conducted using R 3.2.2 (R Development Core Team, 2015).

3 Results

3.1 Soil N-oxide fluxes

In the reference land uses (forest and jungle rubber), N_2O was the dominant N-oxide emitted from soils. In the clay Acrisol landscape, there was a net NO consumption in the soil of the jungle rubber (Table 1). Soil N_2O and NO fluxes from reference land uses were comparable between the two landscapes (P = 0.54–0.74; Table 1; Fig. 1a, b). These fluxes also exemplified high inherent spatial and temporal variations as indicated by their large standard errors.

In the converted land uses (smallholder rubber and oil palm plantations), soil N_2O fluxes were similar to the fluxes of reference land uses (P = 0.58–0.76; Table 1; Fig. 1a, b) within each landscape. However, in the loam Acrisol landscape, the large-scale oil palm plantation PTPN VI had on average 3.5 times higher soil N_2O fluxes than those from the smallholder plantations (Table 1), although this trend was not statistically different (P = 0.15) because of the large variation among replicate plots (as indicated by the large standard error) in this large-scale plantation. Soil NO fluxes, were not different either among land uses in the clay Acrisol landscape (P = 0.73; Table 1). However, in the loam Acrisol landscape, soil NO fluxes were marginally lower (P = 0.07) in rubber plantations (with net NO consumption in the soil) than in jungle rubber (with net NO emission), whereas they were intermediary in forests and oil palm plantations (Table 1).

3.2 Fertilization effects on soil N-oxide fluxes from smallholder oil palm plantations

In comparison to the unfertilized area (chamber location NF at 4–4.5 m from the tree base), soil N_2O fluxes were on average 442 times (clay Acrisol) and 22 times (loam Acrisol) higher within the small fertilized areas around the oil palms (chamber location F2 at 0.8–1 m from the tree base that received 0.32 and 0.26 kg N tree^{-1} in the clay and loam Acrisols, respectively) during the 3 to 8.5 weeks following fertilizer applications (all P < 0.01–0.03; Table 2; Fig. 2c, d). In the chamber location closest to the tree (chamber location F1 at 0.3 m from the tree base), soil N_2O emissions were also 25 times higher compared to the reference chamber location NF in the clay Acrisol landscape (all $P < 0.01$; Table 2; Fig. 2a). In the loam Acrisol landscape, we only detected such an effect in site 2 which displayed 16 times higher soil N_2O emissions in chamber location F1 compared to the reference chamber location NF ($P = 0.03$; Table 2; Fig. 2b).

In the clay Acrisol landscape, soil N_2O emissions in chamber location F2 increased immediately after fertilizer application, reached a peak within 9 days following fertilizer application and stayed elevated for at most 2 months (Fig. 2c). In the loam Acrisol landscape, N_2O fluxes in chamber location F2 increased within the first 5 days, reached maximum fluxes within 5–21 days and remained elevated for at most 6.5 weeks (Fig. 2d). Soil N_2O fluxes in chamber location F1 displayed a similar but less pronounced pattern as those of chamber location F2 in both landscapes (Fig. 2a, b).

Considering the area coverage (4 % of the area in a hectare, based on the number of palms ha^{-1}) and time span of fertilizer-induced N_2O emissions, their average contributions were 21 % to the annual fluxes in the clay Acrisol landscape (with its usual fertilizer application of once a year), and only 6 % to the annual fluxes in the loam Acrisol landscape (with its common fertilizer application of twice a year) (Table 1).

Compared to the unfertilized area (chamber location NF), soil NO fluxes from the fertilized area (chamber location F2) had on average 357 times (clay Acrisol) and 238 times (loam Acrisol) higher fluxes (both $P < 0.01$) during 6 to 8.5 weeks of measurements following fertilizer application (Table 2; Fig. 3c, d). No differences in soil NO fluxes were detected between chamber locations F1 and NF ($P = 0.10$–0.12; Table 2; Fig. 3a, b). Soil NO fluxes in chamber location F2 peaked after 10 days in the loam Acrisol and after 3 weeks in the clay Acrisol landscape (Fig. 3c, d), and returned to the background fluxes after 6–8.5

weeks with a drastic drop after 3–5 weeks (Fig. 3c, d). In chamber location F1, soil NO fluxes increased quickly and decreased to the background fluxes within at most 16 days following fertilizer application (Fig. 3a, b). As was the case for the monthly sampling, soil N_2O fluxes from chamber locations F1 and F2 were larger than soil NO fluxes for both landscapes, (Table 2; Fig. 2a–d and 3a–d). Comparing between landscapes, soil N_2O fluxes from chamber location F2 were higher in the clay than loam Acrisol soils ($P = 0.09$; Table 2; Fig. 2c, d) but were comparable for chamber location F1 ($P = 0.41$; Table 2; Fig. 2a, b) and for soil NO fluxes of both chamber locations (P = 0.45–0.78; Table 2; Fig. 3a–d).

Fertilizer-induced soil NO fluxes in the loam Acrisol landscape were 0.07 ± 0.02 kg NO-N ha^{-1} yr^{-1}, which was roughly the same as our extrapolated annual value of 0.06 ± 0.06 kg NO-N ha^{-1} yr^{-1} from the four measurement periods (Table 1). In the clay Acrisol landscape, fertilizer-induced soil NO fluxes were 0.12 ± 0.04 kg NO-N ha^{-1} yr^{-1}, which was a net emission compared to our extrapolated annual value with a net sink of -0.02 ± 0.11 kg NO-N ha^{-1} yr^{-1}, based on the four measurement periods (Table 1). The percentages of combined soil N_2O and NO fluxes to the applied N fertilizer rate were on average 0.73 % yr^{-1} in the clay Acrisol landscape and 0.20 % yr^{-1} in the loam Acrisol landscape.

3.3 Temporal controls of soil N-oxide fluxes

In the reference land uses, soil N_2O and NO fluxes were both positively correlated with soil NO_3^- contents, while soil NO fluxes were also negatively correlated with WFPS and soil NH_4^+ contents (Table 3). In the converted land uses, soil N_2O fluxes were positively correlated with soil NO_3^- contents (Table 3). There were no significant correlations observed between soil NO fluxes and soil factors in the converted land uses due to the very low NO emissions and even net NO uptake.

From the fertilizer application experiment in the smallholder oil palm plantations, the location directly receiving fertilizer (chamber location F2) showed positive correlations of soil N_2O fluxes with soil NH_4^+ and/or NO_3^- contents in three of the six sites (Table 4). Here, also soil NO fluxes correlated positively with soil NO_3^- contents in the loam Acrisol but not in the clay Acrisol (Table 4). In chamber location F1, positive correlations of soil N_2O fluxes with soil NH_4^+ and/or NO_3^- contents were observed in four of the six sites (Table 4). The correlations of soil N_2O fluxes with mineral N for chamber location F1 in site 2 of the clay Acrisol landscape were caused by one measurement period with very high flux, and exclusion of this observation resulted in a none significant correlation. For soil NO fluxes from chamber location F1, we did not detect any significant correlation with soil factors (Table 4). A positive correlation of soil N_2O fluxes with WFPS was observed for chamber locations F1 and F2 in site 1 of the loam Acrisol landscape, whereas this correlation was negative for chamber location F1 in site 3 of the same landscape (Table 4). We also detected a negative correlation between soil NO fluxes and WFPS for chamber location F2 in site 3 of the clay Acrisol, whereas in the same site soil NO fluxes and WFPS were positively correlated for the unfertilized chamber location NF (Table 4); however this latter correlation was caused by only one sampling time with a high flux and high WFPS.

3.4 Spatial controls of annual soil N_2O fluxes

The soil physical and biochemical characteristics (reported earlier by Allen et al., 2015) that showed significant correlations with annual soil N_2O fluxes are reported in Appendix Table A2. For the reference land uses, annual N_2O fluxes were positively correlated with gross nitrification rates across landscapes (*Spearman's* ρ = 0.57, P = 0.02, n = 16). Within each landscape, annual soil N_2O fluxes from the reference land uses correlated negatively with soil C:N ratio (ρ = -0.69, P = 0.07, n = 8) in the clay Acrisol, whereas in the loam Acrisol annual soil N_2O fluxes correlated positively with microbial C (ρ = 0.69, P = 0.07, n = 8). For the converted land uses, annual N_2O fluxes correlated negatively with sand content across landscapes (ρ = -0.57, P = 0.06, n = 12). There were no other correlations detected with any other soil biochemical parameters.

4 Discussion

4.1 Soil N_2O and NO fluxes from the reference land uses

The N_2O fluxes from our forest soils (Table 1) fell at the lower end of those reported for humid tropical forests (10–85 µg N_2O-N m^{-2} h^{-1}; summarized by Castaldi et al., 2013). Compared to soil N_2O fluxes measured in Indonesia, our values were comparable to those reported for montane forests on Cambisol soil with similar sampling frequency and spatial replication (13 µg N_2O-N m^{-2} h^{-1}; Purbopuspito et al., 2006) and to five lowland forest stands on Acrisol soil measured once (12 µg N_2O-N m^{-2} h^{-1}; Ishizuka et al., 2005). However, soil N_2O fluxes from our forests were lower than those reported for montane forests on Cambisol soils with six monthly measurements and comparable replication (25 µg N_2O-N m^{-2} h^{-1}; Veldkamp et al., 2008) and from a lowland forest on Ferralsol soil with 13 measurements at monthly interval (20 µg N_2O-N m^{-2} h^{-1}; Aini et al., 2015). In contrast, our values were higher than those reported for two lowland forests on Ferralsol soil with nine measurements at monthly interval (3 µg N_2O-N m^{-2} h^{-1}; Ishizuka et al., 2002). Since the studies from the montane forests were conducted on fertile, less-weathered Cambisol soils and the studies within the same region (Jambi province) by Ishizuka et al. (2002, 2005) and Aini et al. (2015) have less sampling frequency or spatial replication, their values should be carefully related to our measured fluxes.

Soil NO fluxes from Southeast Asian lowland forests are not reported so far. Our measured NO fluxes from the forest soils (Table 1) tended to be lower than those reported for lowland forests in Latin America with soils ranging from less weathered Cambisols to highly weathered Acrisols and Ferralsols (from 3–90 µg NO-N m^{-2} h^{-1}; Corre et al., 2014; Davidson et al., 2004; Keller et al., 2005; Verchot et al., 1999). There are only two studies conducted in Indonesia that reported soil NO fluxes from montane forests on Cambisol soils (Purbopuspito et al., 2006, Veldkamp et al., 2008). Our measured soil NO fluxes were comparable with the values reported for montane forests at ≥ 1800 m elevation (2 µg NO-N m^{-2} h^{-1}; Purbopuspito et al., 2006) but lower than those reported for (pre)montane forests (6–12 µg NO-N m^{-2} h^{-1}; Purbopuspito et al., 2006; Veldkamp et al., 2008). Although it is known that tropical forest soils are the largest natural source of N_2O and produce considerable amounts of NO, our measurements from these lowland forests in Jambi, Indonesia on highly weathered Acrisol soils showed generally low soil N-oxide fluxes.

In contrast to our first hypothesis (H1), soil N-oxide fluxes from the reference land uses were comparable between loam and clay Acrisol landscapes. This is possibly due to the generally low soil N availability in these sites, as indicated by their lower gross N mineralization rates (Allen et al., 2015) compared, for example, to the less weathered Cambisol and Nitisol soils in a lowland forest of Panama (Corre et al., 2010). Soil N-oxide fluxes are largely controlled, first, by the magnitude of soil N availability, as depicted in the HIP conceptual model (Davidson et al., 2000). This influence of soil N availability on N-oxide fluxes was illustrated by the positive correlations of soil N-oxide fluxes with soil NO_3^- contents (Table 3). Across landscapes, this first level of control was also corroborated by the positive correlations of annual soil N_2O fluxes with gross nitrification rates, and within each landscape by the negative correlation with the soil C:N ratio (clay Acrisol landscape) and by the positive correlation with microbial C (loam Acrisol landscape) (see Sect. 3.4). Our findings were consistent with those from other tropical soils, illustrating that soil N-oxide fluxes across or within sites are controlled by soil N availability as expressed in various indexes such as soil NO_3^- contents (Keller and Reiners, 1994; Müller et al., 2015), nitrification rates (Davidson et al., 2000) and soil C:N ratio (Breuer et al., 2000).

Moreover, we attributed the low soil NO fluxes and the dominance of N_2O (Table 1) in our sites to the second level of control of N-oxide fluxes - soil aeration status (HIP model; Davidson et al., 2000). The ratio of N_2O to NO is expected to increase when WFPS exceeds 60 % as low soil aeration favors N_2O production by denitrification and nitrification processes (Davidson et al., 2000). WFPS in the reference land uses were ≥ 60 % (Appendix Table A3, except in jungle rubber of the loam Acrisol with 54 % WFPS). Hence, it was not surprising that our measured soil NO fluxes were close to zero or showed net consumption (Table 1); the high WFPS may have led to NO reduction to N_2O (Conrad, 1996; Pilegaard, 2013). This was supported by the negative correlation between soil NO fluxes and WFPS (Table 3). Furthermore, increased concentrations of NO in the atmosphere due to biomass burning in this region (Field et al., 2009; Levine, 1999), which also occurred in 2013 (Gaveau et al., 2014), may have resulted in a net NO consumption (not only in the reference land uses but also in the converted land uses; Table 1) since increased ambient NO concentration could enhanced soil NO uptake (Conrad, 1994). In summary, soil NO fluxes from the reference land uses were of minor importance compared to soil N_2O fluxes. However, if droughts will occur more frequently or extremely in this region (Lestari et al., 2014), soil NO fluxes might become important.

4.2 Land-use change effects on soil N_2O and NO fluxes

Soil N_2O fluxes from our unfertilized rubber plantations (Table 1) were comparable to a rubber plantation on Ferralsol soil in Malaysia with eight measurements during 1.5-year period (8 µg N_2O-N m^{-2} h^{-1}, fertilized with 9 kg N ha^{-1} yr^{-1}; Yashiro et al., 2008) and slightly higher than fluxes reported from a rubber plantation on a lateritic soil in China with only two months of measurement (4 µg N_2O-N m^{-2} h^{-1}, fertilized with 55 kg N ha^{-1} yr^{-1}; Werner et al., 2006). Studies from the same region (Jambi, Indonesia) report either lower soil N_2O fluxes from a rubber plantation on Ferralsol soil with nine sampling days at monthly interval (1 µg N_2O-N m^{-2} h^{-1}; Ishizuka et al., 2002) or higher fluxes from five rubber plantations on Acrisol soils with only one-time measurement (21 µg N_2O-N m^{-2} h^{-1}; Ishizuka et al., 2005) and from one rubber plantation on Ferralsol soil with 13 sampling days at monthly interval (12 µg N_2O-N m^{-2} h^{-1}; Aini et al., 2015). The rubber plantations in these latter three studies were all not fertilized. Soil N_2O fluxes from our oil palm plantations (Table 1), which had fertilization of 48–88 kg N ha^{-1} yr^{-1}, were in the same order of magnitude as those reported from three fertilized oil palm plantations on Acrisol soils in Jambi, Indonesia with only one-time measurement (15 µg N_2O-N m^{-2} h^{-1}; Ishizuka et al., 2005) and from one unfertilized oil palm plantation on Cambisol soil in Jambi, Indonesia with 13 monthly measurements (12 µg N_2O-N m^{-2} h^{-1}; Aini et al., 2015). However, soil N_2O fluxes from our oil palm sites were higher compared to one oil palm plantation on Ferralsol soil in Malaysia with eight measurements during 1.5-year period (-0.1 µg N_2O-N m^{-2} h^{-1}, fertilized with 25 kg N ha^{-1} yr^{-1}; Yashiro et al., 2008). Soil NO fluxes have never been reported from rubber or oil palm plantations.

In contrast to our second hypothesis (H2), soil N-oxide fluxes were comparable among land uses (except for soil NO fluxes between rubber and jungle rubber in the loam Acrisol landscape as discussed below), even with the observed decreases in soil mineral N levels among land uses (i.e., generally lower NH_4^+ and NO_3^- levels in rubber plantations than in the reference land uses at both landscapes; Appendix Table A3). In the same study sites, Allen et al. (2015) found differences in other indices of soil N availability with land-use change, particularly in the clay Acrisol landscape: microbial C and N, gross N mineralization and

NH_4^+ immobilization rates decrease with conversion of forest to rubber or oil palm plantations. N-oxide emissions generally account only a small fraction of soil available N (e.g., N_2O + NO emissions comprise 0.03 % of gross N mineralization rates in a lowland forest on Cambisol and Nitisols soils in Panama; Corre et al., 2014). In our present study, the reference land uses on highly weathered Acrisol soils have low soil N availability and their conversion to these plantations further decreases the soil N-cycling rates (Allen et al., 2015). Hence, we reason that we did not detect differences in N-oxide fluxes with land-use conversion to rubber and oil palm plantations because we started with low soil N availability and low N-oxide emissions and any changes were probably too small to detect statistically. The temporal pattern of soil N_2O fluxes in the converted land uses were also controlled by soil NO_3^- contents (Table 3), emphasizing the first level of control of soil N availability on soil N_2O fluxes (HIP model; Davidson et al., 2000). Across landscapes, the correlations of annual soil N_2O fluxes from these converted land uses with sand contents (see Sect. 3.4) also suggested the indirect influence of soil texture on water holding capacity, or conversely soil aeration status, which is the second level of control on soil N_2O fluxes (HIP model). Consequently, the soil N-oxide emission footprint of smallholder oil palm and rubber plantations was similar to the original land uses (Table 1). This finding was in contrast to a study by Hewitt et al. (2009) conducted in Sabah, Malaysian Borneo, wherein they showed that oil palm plantations emit more N-oxides than rainforests, which may be explained by their higher fertilization rate (500 kg N ha^{-1} yr^{-1}) compared to our smallholder oil palm plantations (48-88 kg N ha^{-1} yr^{-1}). Thus, an increase in fertilizer usage, e.g., in large-scale plantations in our study region, might change this soil N-oxide emission footprint drawn mainly from smallholder plantations (see Sect. 4.3).

The lower soil NO fluxes in rubber compared to jungle rubber in the loam Acrisol (Table 1) partly supports our second hypothesis. These differences might be related to the high soil NO_3^- contents and low WFPS in jungle rubber (Appendix Table A3), which could favor its relatively high soil NO emissions; this was also supported by the opposing correlations of soil NO flux with soil NO_3^- and WFPS (Table 3). Additionally, the low soil NO fluxes from rubber plantations could be the result of the effect of monoterpenes, produced by rubber trees, which reduce nitrification in soil (Wang et al., 2007; White, 1991). This is supported by low gross nitrification rates (measured in the same plots by Allen et al., 2015), low soil NO_3^- contents (Appendix Table A3) and consequently low soil NO fluxes in rubber plantations (Table 1).

4.3 Soil management effects on soil N_2O and NO fluxes from oil palm plantations

N fertilizer application, a commonly employed soil management in oil palm plantations (e.g., Allen et al., 2015; Hassler et al., 2015), increases N-oxide emission for a relatively short period (e.g., Koehler et al. 2009). Our findings show that these fertilizer-induced N-oxide emissions were mainly limited to the small area around the palm base where fertilizer was commonly applied (4 % of the area in a hectare) and that N-oxide emissions peaked within 3 weeks (Figs. 2 and 3). These N-fertilizer induced N_2O fluxes of 6–21 % of the annual soil N_2O fluxes were similar in magnitude as the standard errors of the annual fluxes (estimated from the monthly measurements; Table 1). Thus, inclusion of these N-induced emissions in our annual estimates did not result in statistically significant effects of land-use change.

The percentages of soil N_2O and NO fluxes to the applied N fertilizer rate were smaller than those reported from other agricultural land uses in humid tropical regions (6.4–8.6 %; Veldkamp and Keller, 1997; Veldkamp et al., 1998). Usually the percentage of soil N-oxide emissions to applied N fertilizer rate increases with increasing N fertilization rates (Hoben et al., 2011; Pennock and Corre, 2001). Since the fertilization rates in our studied smallholder oil palm plantations (48–88 kg N ha^{-1} yr^{-1}) were lower compared to the fertilization rates in these other studies (300–360 kg N ha^{-1} yr^{-1}; Veldkamp and Keller, 1997; Veldkamp et al., 1998), our quantified N-oxide loss from N fertilizer were also low. The relatively high soil N_2O fluxes from the large-scale oil palm plantation PTPN VI, although not statistically different from the smallholder plantations (Table 1), could be attributed to its high N fertilization rate (196 kg N ha^{-1} yr^{-1}). Summing the fertilizer-induced N-oxide fluxes and the annual soil N-oxide emissions based on the monthly measurements (Table 1), these values from the smallholder plantations were low relative to the annual flux from the large-scale plantation (Table 1). Based on our finding that soil N_2O fluxes following fertilizer application (chamber location F2) were higher in the clay than loam Acrisol landscapes (most likely due to higher WFPS in the clay (61 ± 8 %) than loam Acrisol (27 ± 3 %) during this measurement period), soil N-oxide fluxes from large-scale plantations on clay soils could be even higher than what we measured here from a large-scale plantation on a loam soil. Our findings reinforced the need to quantify these climate-relevant N-oxide gases in large-scale plantations, which constitute ~50 % of the land area under oil palm plantation in whole of Sumatra (BPS, 2014).

Temporal patterns of soil N-oxide fluxes following fertilizer application were also controlled by soil N availability, as reflected by their positive correlations with soil NH_4^+ and/or NO_3^- contents (Table 4). The application of N fertilizer provides temporary surplus of mineral N that was lost via gaseous emission and leaching (Kurniawan, 2016), and such effect diminished with time as the mineral N is incorporated into the soil N-cycling processes (Allen et al., 2015). The positive correlation between soil N_2O fluxes and WFPS (i.e., chamber locations F1 and F2 in site 1 of the loam Acrisol; Table 4) and the negative correlation between soil NO fluxes and WFPS (i.e., chamber location F2 in site 3 of the clay Acrisol landscape; Table 4) again attested that when the first level of control (soil N availability) was favorable (i.e., high soil mineral N contents in these fertilized chamber locations) the control of soil moisture on aeration status was enhanced, as such correlation was not seen in the unfertilized area (chamber location NF) or in the monthly measured fluxes (Tables 3 and 4). These correlations indicated that following fertilizer application soil NO fluxes decreased whereas soil N_2O fluxes increased with increase in WFPS. In site 3 of the loam Acrisol, the seemingly contradicting negative correlation of soil N_2O fluxes with WFPS (Table 4) was only because there was a decreasing WFPS following fertilizer application with concurrently increasing soil mineral N contents - the latter dominantly driving the increases in soil N_2O fluxes (i.e., positive correlations with NH_4^+ and NO_3^-; Table 4). In summary, the short-term effect of fertilization also depicted the two levels of controls on soil N-oxide fluxes as exemplified in the HIP model.

5 Conclusions

Our study provides the first spatially replicated study with a full year of measurements (at monthly interval) of soil N_2O fluxes and the first reported soil NO fluxes from this region of hotspot of land-use conversion for globally important tree cash crops. In contrast to our first hypothesis (H1), soil texture, through its role on soil fertility, did not directly affect soil N-oxide fluxes (as shown by the comparable fluxes between landscapes with soil textural differences) but indirectly influenced the landscape-scale pattern of annual soil N_2O fluxes in the converted land uses (i.e., negative correlation between annual N_2O fluxes and sand content) most likely through its role on soil moisture availability. The generally low soil N-oxide fluxes from the reference land uses were due to the low soil N availability in these highly weathered Acrisol soils (Allen et al., 2015). Forest or jungle rubber conversion to rubber and oil palm by smallholders also did not show significant changes in soil N-oxide fluxes, except for the decrease in soil NO fluxes in rubber plantations and for the short-term pulse of soil N-oxide fluxes following fertilizer application in oil palm plantations. These partly support our second hypothesis (H2). Using a conservative estimate of N-oxide (N_2O + NO) loss from the applied N fertilizer in oil palm plantations (average of 0.5 % from the loam and clay Acrisol landscapes), and a conservative average N fertilization rate across smallholder and large-scale plantations of 100 kg N ha^{-1} yr^{-1}, with the total land area of oil palm in Jambi province of 721000 ha (BPS, 2014), we estimated an annual soil N-oxide emission from N fertilization of 361 tons N yr^{-1}. The N fertilization rates in our smallholder oil palm plantations were only about one-fourth to one-half of what is commonly practiced in large-scale industrial plantations (e.g., 130–260 kg N ha^{-1} yr^{-1} in Jambi, Indonesia; Pahan, 2010), and our measurements from a large-scale oil palm plantation PTPN VI showed relatively high soil N-oxide fluxes. To improve estimate of soil N-oxide fluxes at regional level, future studies should focus on large-scale plantations (which constitute 38 % of oil palm land area in Jambi province; BPS, 2014) with frequent measurements during 2 months following fertilizer application, and particularly during wet season for N_2O flux measurements and during dry season for NO flux measurements.

Data availability

The underlying research data of this study is deposited at the EFForTS-IS data repository (https://efforts-is.uni-goettingen.de), an internal data exchange-platform, which is accessible for SFB 990 members only. Based on data sharing agreement within the SFB 990, these data are currently not publicly accessible but will be made available through a written request to the senior authors.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. Mean (±SE, $n = 4$ sites) soil N_2O (with 12 monthly measurements) and NO fluxes (with four monthly to bimonthly measurements) and annual soil N_2O fluxes from different land uses within each landscape in Jambi, Indonesia. Means followed by different lowercase letters indicate significant differences among land uses within each landscape and different capital letters indicate significant differences between landscapes within each land use (linear mixed-effect models with Fisher's LSD test at $P \leq 0.09$). For soil NO fluxes in the clay Acrisol, forest was excluded in the comparison among land uses because measurements were only carried out in two sites. Annual soil N_2O fluxes are calculated from the monthly fluxes using trapezoidal rule. For smallholder oil palm plantations, values in italics were the fertilizer-induced annual soil N_2O fluxes (see Sect. 2.2). In the loam Acrisol landscape, soil N_2O fluxes were additionally measured in a large-scale oil palm plantation (mean±SE, $n = 4$ replicates); these fluxes did not differ from those of smallholder plantations within the same landscape (linear mixed-effect models with Fisher's LSD test at $P = 0.15$).

Land-use type	N_2O fluxes ($\mu g\ N\ m^{-2}\ h^{-1}$)	NO fluxes ($\mu g\ N\ m^{-2}\ h^{-1}$)	Annual N_2O fluxes ($kg\ N\ ha^{-1}\ year^{-1}$)
clay Acrisol landscape			
Forest	$12.8 \pm 5.6^{a,A}$	(1.7 ± 0.3)	1.0 ± 0.4
Jungle rubber	$6.7 \pm 1.5^{a,A}$	$-0.6 \pm 0.7^{a,A}$	0.6 ± 0.1
Rubber	$5.6 \pm 2.5^{a,A}$	$-1.0 \pm 0.2^{a,A}$	0.5 ± 0.2
Oil palm (smallholder plantation)	$11.5 \pm 2.9^{a,A}$	$-0.2 \pm 1.2^{a,A}$	1.0 ± 0.3 *0.2 ± 0.0*
loam Acrisol landscape			
Forest	$9.8 \pm 1.5^{a,A}$	1.9 ± 1.3^{ab}	0.9 ± 0.2
Jungle rubber	$14.0 \pm 6.7^{a,A}$	$5.7 \pm 5.8^{a,A}$	1.2 ± 0.6

Rubber	$8.6 \pm 2.0^{a,A}$	$-1.2 \pm 0.5^{b,A}$	0.7 ± 0.2
Oil palm (smallholder plantation)	$12.2 \pm 6.1^{a,A}$	$0.7 \pm 0.7^{ab,A}$	1.1 ± 0.5 *0.1 ± 0.0*
Oil palm (large-scale plantation)	$42.3 \pm 24.2^{a,A}$	-	3.3 ± 1.7

Table 2. Mean (±SE, *n* = 3 oil palm trees) soil N_2O and NO fluxes from three chamber locations during a fertilization in three (for N_2O) or one (for NO) smallholder oil palm plantation within each landscape, measured 6 to 11 times during 3–8.5 weeks following fertilization. Means followed by different letters indicate significant differences among chamber locations within each site (linear mixed-effect models with Fisher's LSD test at $P \leq 0.05$). Chamber F1, F2 and NF were placed at 0.3 m (with incidental fertilization), 0.8 m (fertilized area), and 4–4.5 m (non-fertilized area, serving as the reference chamber), respectively, from the stem base. 0.32 kg N tree^{-1} was applied in the clay Acrisol and 0.26 kg N tree^{-1} in the loam Acrisol in accordance to the smallholders' practices.

Oil palm site	Chamber location	N_2O fluxes (µg N m^{-2} h^{-1})	NO fluxes (µg N m^{-2} h^{-1})
		clay Acrisol landscape	
1	F1	156.7 ± 86.8^{b}	-
	F2	910.1 ± 410.0^{a}	-
	NF	6.9 ± 3.3^{c}	-
2	F1	130.6 ± 34.6^{b}	-
	F2	692.7 ± 144.1^{a}	-
	NF	9.9 ± 3.0^{c}	-
3	F1	45.5 ± 3.7^{b}	4.7 ± 1.7^{b}
	F2	1281.0 ± 486.7^{a}	535.3 ± 194.5^{a}
	NF	1.1 ± 1.6^{c}	1.5 ± 1.5^{b}
Oil palm site	Chamber location	N_2O fluxes (µg N m^{-2} h^{-1})	NO fluxes (µg N m^{-2} h^{-1})
		loam Acrisol landscape	

1	F1	33.5 ± 9.8^{b}	-
	F2	133.4 ± 34.9^{a}	-
	NF	11.8 ± 6.1^{b}	-
2	F1	129.7 ± 46.2^{a}	46.2 ± 19.6^{b}
	F2	205.3 ± 24.2^{a}	157.1 ± 35.7^{a}
	NF	7.9 ± 4.8^{b}	0.7 ± 0.3^{b}
3	F1	5.2 ± 1.0^{b}	-
	F2	104.5 ± 81.9^{a}	-
	NF	3.7 ± 1.7^{b}	-

Table 3. Pearson correlation coefficients between soil N_2O flux (n = 48; µg N m^{-2} h^{-1}), soil NO flux (n = 16; µg N m^{-2} h^{-1}), water-filled pore space (WFPS; %, top 0.05 m depth), soil temperature (°C, top 0.05 m depth) and extractable mineral N (mg N kg^{-1}, top 0.05 m depth) across landscapes for the reference and converted land uses. Correlation was conducted using the means of the four replicate plots per land use on each of the 12 monthly measurements (for soil N_2O fluxes) and four monthly to bimonthly measurements (for soil NO fluxes).

Land-use type	Variable	WFPS	Soil temp.	NH_4^+	NO_3^-
Reference land uses (forest and jungle rubber)	Soil N_2O flux	-0.21	-0.09	-0.23	0.38^c
	Soil NO flux	-0.74^c	-0.15	-0.48^a	0.69^c
Converted land uses (rubber and oil palm)	Soil N_2O flux	0.11	0.15	0.23	0.37^c
	Soil NO flux	-0.05	0.09	-0.05	0.23

$^aP \leq 0.09$, $^bP \leq 0.05$, $^cP \leq 0.01$.

Table 4. Pearson correlation coefficients (*n* = 6–11 measurements following fertilization) between N-oxide fluxes (μg N m^{-2} h^{-1}), water-filled pore space (WFPS; %, top 0.05m depth) and extractable mineral N (mg N kg^{-1}, top 0.05 m depth), measured at different chamber locations (F1, F2 and NF were at 0.3 m (with incidental fertilization), 0.8 m (fertilized area) and 4–4.5 m (non-fertilized area), respectively, from the stem base). Correlation was conducted using the means of the three replicate trees per chamber location on each sampling day following fertilization.

Oil palm plantation site	Chamber location	Variable	WFPS	NH_4^+	NO_3^-
clay Acrisol landscape					
1 (*n* = 6 measurements)	F1	Soil N_2O flux	0.55	0.88[b]	0.46
	F2		0.57	-0.22	-0.31
	NF		0.37	-0.64	-0.44
2 (*n* = 11 measurements)	F1	Soil N_2O flux	0.11	0.93[c]	0.95[c]
	F2		0.08	0.05	-0.06
	NF		0.09	-0.44	-0.45
3 (*n* = 10 measurements)	F1	Soil N_2O flux	-0.19	0.10	0.09
	F2		0.05	0.86[c]	0.85[c]
	NF		-0.32	0.06	-0.44
3 (*n* = 10 measurements)	F1	Soil NO flux	-0.34	0.44	0.48
	F2		-0.61[a]	0.10	-0.04
	NF		0.59[a]	-0.14	-0.13
loam Acrisol landscape					
1 (*n* = 6 measurements)	F1	Soil N_2O flux	0.96[c]	-0.18	0.03
	F2		0.78[a]	0.61	-0.40
	NF		-0.06	-0.29	<0.01
2 (*n* = 9	F1	Soil N_2O flux	-0.55	0.71[b]	-0.03
	F2		0.35	-0.20	0.89[c]

measurements)	NF		0.34	<0.01	-0.35
3 (*n* = 11 measurements)	F1	Soil N_2O flux	-0.68[b]	0.67[b]	0.62[b]
	F2		-0.27	-0.2	0.57[a]
	NF		0.36	0.19	0.06
2 (*n* = 9 measurements)	F1	Soil NO flux	-0.07	0.18	-0.27
	F2		0.07	-0.11	0.96[c]
	NF		-0.16	0.12	-0.23

[a] $P \leq 0.09$, [b] $P \leq 0.05$, [c] $P \leq 0.01$.

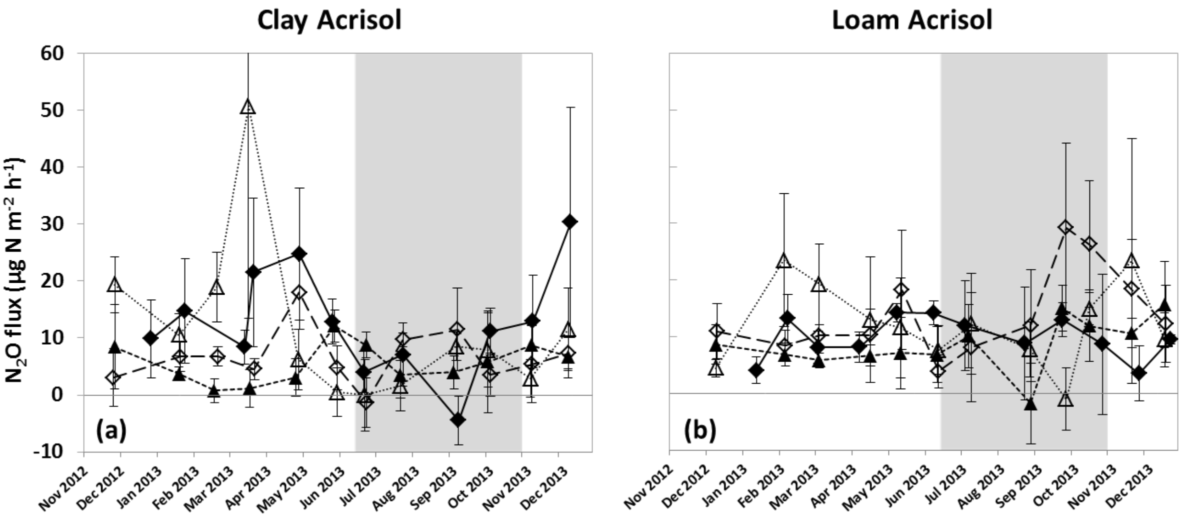

Figure 1. Mean (±SE, *n* = 4 sites) soil N$_2$O fluxes from forest (◆), jungle rubber (◇), rubber (▲) and oil palm (△), located within the clay (**a**) and loam Acrisol (**b**) landscapes in Jambi, Indonesia. Measurements were carried out monthly from December 2012 to December 2013; grey shadings mark the dry season.

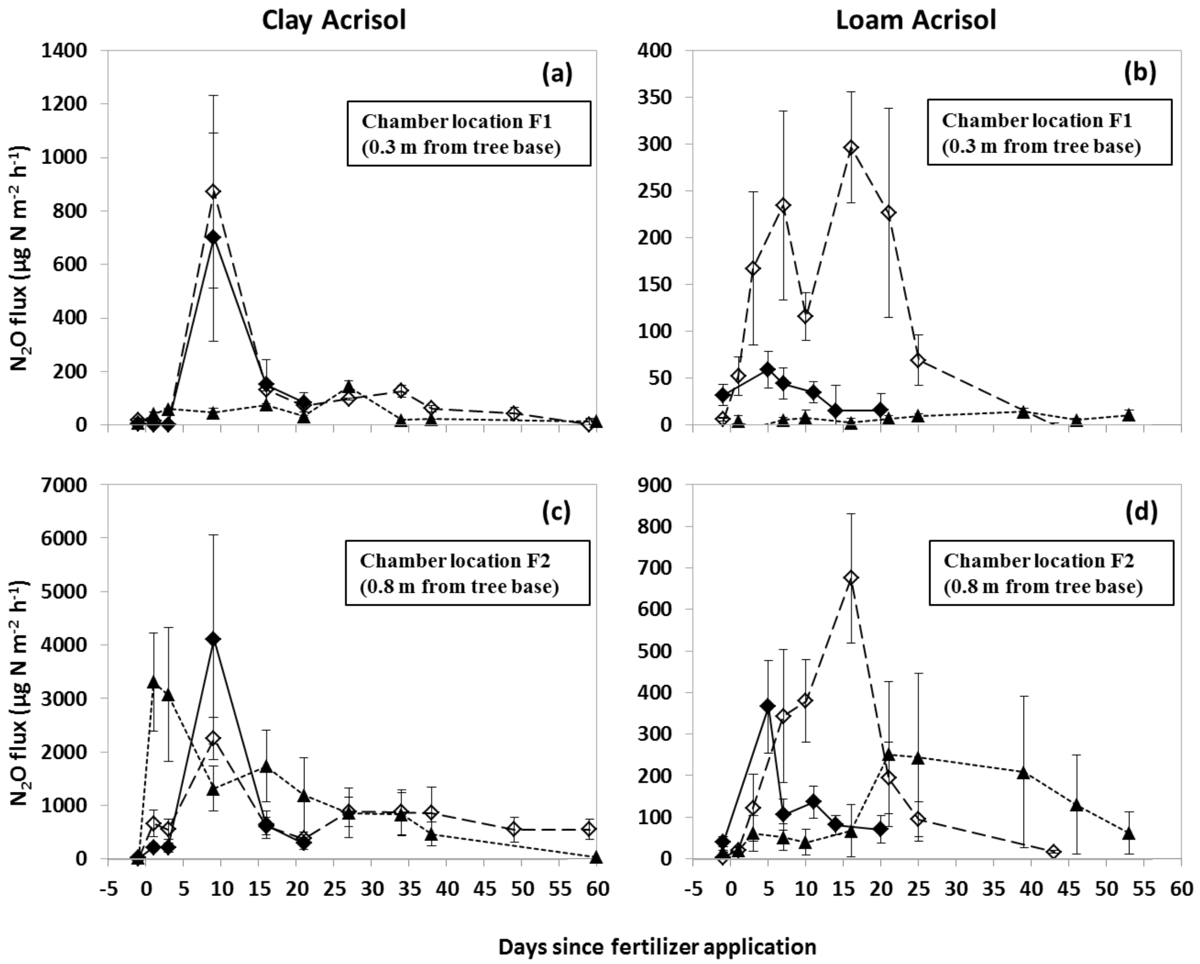

Figure 2. Mean (±SE, *n* = 3 oil palm trees) soil N_2O fluxes during a fertilization in smallholder oil palm plantations 1 (◆), 2 (◇) and 3 (▲) in the clay (**a** and **c)** and loam Acrisol (**b** and **d**) landscapes. Smallholders fertilized around the base of each tree at about 0.8–1 m from the tree base. Fluxes were measured at F1 = 0.3 m from the tree base (**a** and **b**) and at F2 = 0.8 m from the tree base on the fertilized location (**c** and **d**) with 0.32 kg N tree^{-1} in the clay Acrisol and 0.26 kg N tree^{-1} in the loam Acrisol in accordance to the smallholders' practices.

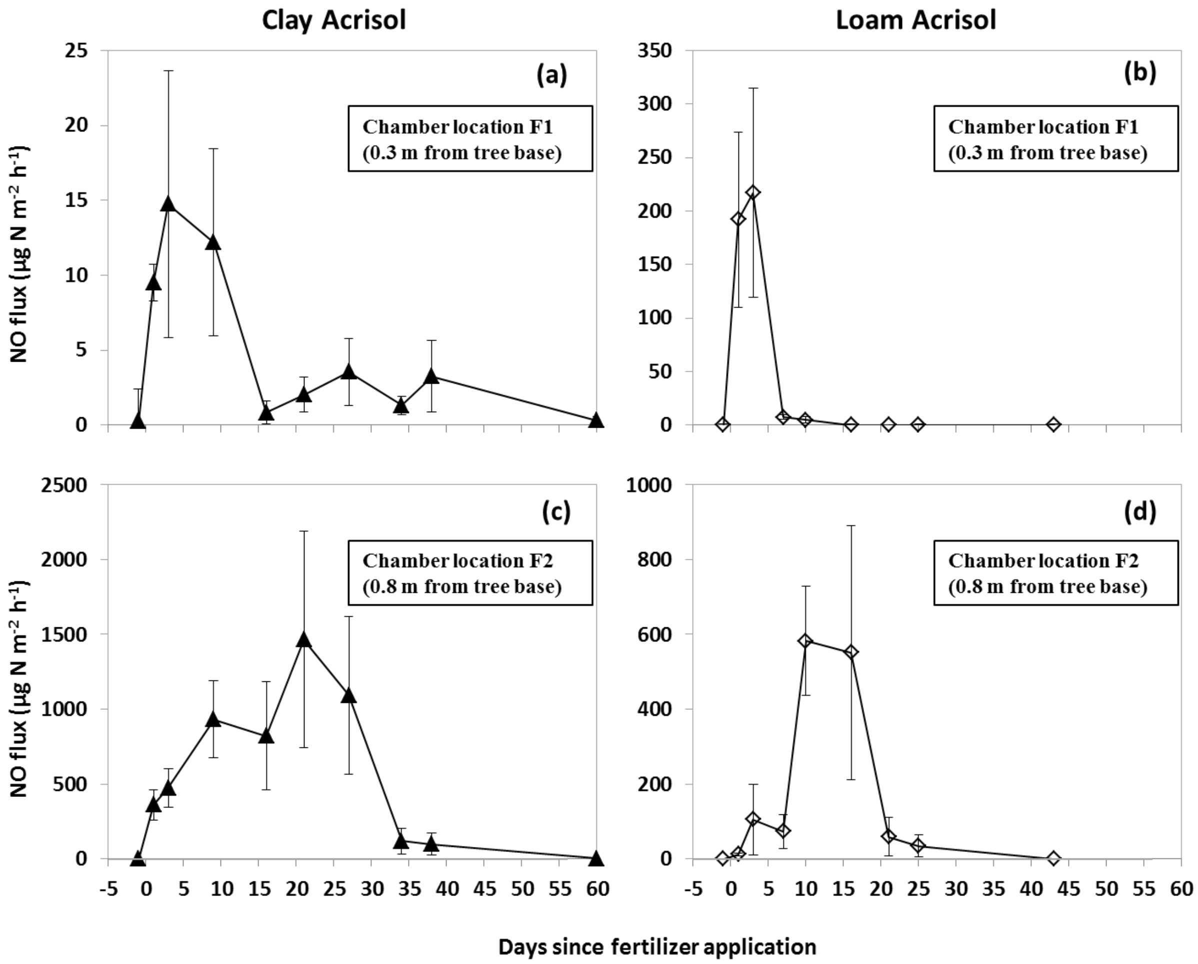

Figure 3. Mean (±SE, *n* = 3 oil palm trees) soil NO fluxes during a fertilization in a smallholder oil palm plantation in the clay (**a** and **c)** and loam Acrisol (**b** and **d**) landscapes. Smallholders fertilized around the base of each tree at about 0.8–1 m from the tree base. Fluxes were measured at F1 = 0.3 m from the tree base (**a** and **b**) and at F2 = 0.8 m from the tree base on the fertilized location (**c** and **d**) with 0.32 kg N tree^{-1} in the clay Acrisol and 0.26 kg N tree^{-1} in the loam Acrisol in accordance to the smallholders' practices.

Appendix A: Detailed description of the linear mixed-effect models application

For analysis of differences in N-oxide fluxes among land uses or between soil landscapes, we used the means of the four chambers representing each replicate plot on a sampling day. Linear mixed-effect (LME) models (Crawley, 2007) were used to assess differences between landscapes for the reference land uses (testing H1) or differences among land uses within each landscape (testing H2). In the LME models, either landscape or land use was considered as fixed effect whereas replicate plots and sampling days were considered as random effects. For comparison of soil N_2O fluxes between the large-scale (PTPN VI) and smallholder oil palm plantations within the loam Acrisol landscape, we also used the means of the three chambers per replicate plot on each sampling day in the PTPN VI site, as there were no significant differences between these chamber locations (based on LME models with chamber location as fixed effect and replicates as well as sampling days as random effects; $P = 0.70$). We then used the LME model with plantation types (i.e., large scale vs. smallholder) as a fixed effect and replicates and sampling days as random effects. For analysis of fertilization (i.e., as represented by the chamber locations F1, F2 and NF) on soil N-oxide fluxes from smallholder oil palm plantations, this was conducted for each site with oil palm trees as replicates. In the LME model for this experiment, chamber location was the fixed effect whereas replicate palm trees and sampling days were the random effects. To assess differences in N-oxide fluxes between landscapes following fertilization for chamber locations F1 and F2, we also used LME models with landscape as fixed effect and with replicate plots (for N_2O) or replicate palm trees (for NO) and sampling days as random effects. In all LME models, we included (1) a variance function that allows different variances of the fixed effect, and/or (2) a first-order temporal autoregressive function to account for decreasing correlation between sampling days with increasing time difference, if these functions improved the relative goodness of the model fit based on the Akaike information criterion.

Table A1. Location and year of measurement.

Measurement	Sampling location	N-oxide determined	Measurement year
clay Acrisol landscape			
Four land uses (forest, jungle rubber, rubber, oil palm)	all 16 replicate plots	N_2O and NO	2013
Intensive measurements following fertilization (oil palm)	three oil palm replicate plots	N_2O	2013–2014
Intensive measurements following fertilization (oil palm)	one oil palm replicate plot	NO	2013
loam Acrisol landscape			
Four land uses (forest, jungle rubber, rubber, oil palm)	all 16 replicate plots	N_2O and NO	2013
Intensive measurements following fertilization (oil palm)	three oil palm replicate plots	N_2O	2013-2014
Intensive measurements following fertilization (oil palm)	one oil palm replicate plot	NO	2013
Large-scale oil palm plantation	PTPN VI	N_2O	2014-2015

Table A2. Mean (±SE, *n* = 4 sites) soil physical and biochemical characteristics in the top 0.10 m depth (except sand content with *n* = 3 sites) from different land uses within each landscape in Jambi, Sumatra, Indonesia. These soil factors and gross nitrification were reported by Allen et al. (2015).

Soil characteristics	Land-use type			
	Forest	Jungle rubber	Rubber	Oil palm
clay Acrisol landscape				
Sand (%)	36 ± 11	27 ± 20	35 ± 7	11 ± 2
Soil C:N ratio	13.1 ± 1.3	13.0 ± 0.3	14.3 ± 0.6	13.5 ± 0.2
Microbial C (mg C kg^{-1})	1048 ± 20	922 ± 223	561 ± 61	617 ± 112
Gross nitrification rate (mg N kg^{-1} day^{-1})	0.9 ± 0.3	1.0 ± 0.2	0.7 ± 0.2	2.0 ± 0.8
loam Acrisol landscape				
Sand (%)	39 ± 8	42 ± 19	26 ± 13	43 ± 14
Soil C:N ratio	14.3 ± 0.2	13.7 ± 0.8	11.7 ± 0.7	12.5 ± 0.5
Microbial C (mg C kg^{-1})	514 ± 48	578 ± 45	461 ± 58	403 ± 24
Gross nitrification rate (mg N kg^{-1} day^{-1})	1.9 ± 0.4	0.9 ± 0.2	0.9 ± 0.2	1.2 ± 0.5

Table A3. Mean (±SE, $n = 4$ sites) soil water-filled pore space (WFPS) and extractable mineral N in the top 0.05 m depth for different land uses within each landscape in Jambi, Sumatra, Indonesia. Means followed by different lowercase letters indicate significant differences among land uses within each landscape and different capital letters indicate significant differences between landscapes within each land use (linear mixed-effect models with Fisher's least significant difference (LSD) test at $P \leq 0.05$). These soil factors were reported by Hassler et al. (2015).

Land-use type	WFPS (%)	NH_4^+ (mg N kg^{-1})	NO_3^- (mg N kg^{-1})
clay Acrisol landscape			
Forest	$73.0 \pm 12.3^{a,A}$	$7.0 \pm 1.0^{a,A}$	$2.2 \pm 0.4^{a,A}$
Jungle rubber	$86.7 \pm 5.9^{a,A}$	$7.3 \pm 0.2^{a,A}$	$0.2 \pm 0.1^{b,B}$
Rubber	$61.5 \pm 7.4^{a,A}$	$4.3 \pm 0.2^{b,A}$	$0.1 \pm 0.0^{b,B}$
Oil Palm	$74.0 \pm 7.3^{a,A}$	$5.8 \pm 0.6^{a,A}$	$0.8 \pm 0.5^{b,}$
loam Acrisol landscape			
Forest	$64.0 \pm 3.3^{a,A}$	$5.9 \pm 0.4^{a,A}$	$0.6 \pm 0.2^{ab,B}$
Jungle rubber	$53.9 \pm 3.7^{a,B}$	$5.6 \pm 0.3^{a,B}$	$1.3 \pm 0.6^{a,A}$
Rubber	$72.6 \pm 5.7^{a,A}$	$4.1 \pm 0.6^{b,A}$	$0.1 \pm 0.0^{b,A}$
Oil Palm	$59.0 \pm 6.7^{a,A}$	$4.2 \pm 1.1^{b,B}$	$0.6 \pm 0.4^{ab,B}$